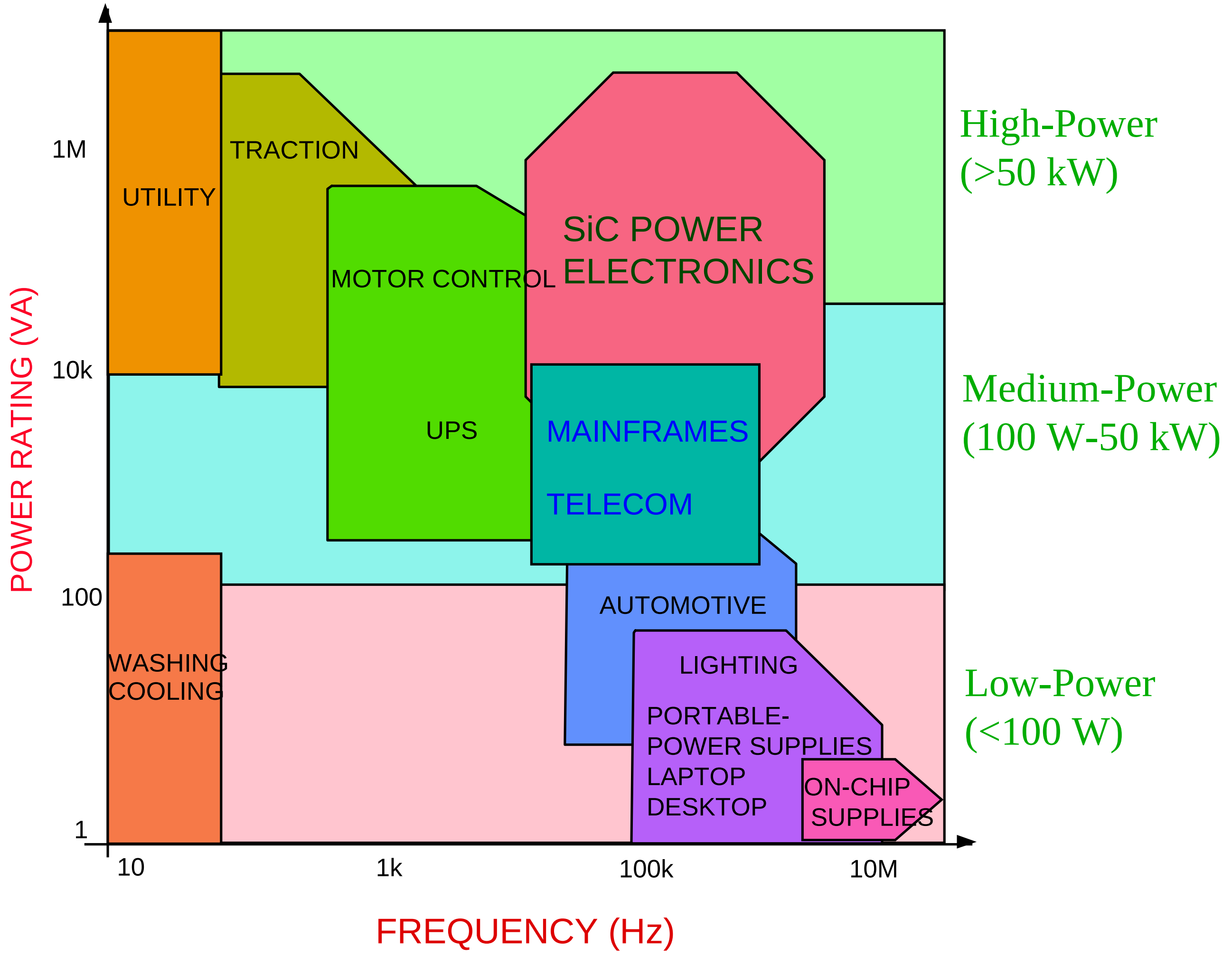
Evaluation of SiC Diodes for SMPS Applications

Prof. K Shenai

PERG Power Electronics Reliability Group

Electrical Engineering and Computer Science
University of Illinois at Chicago

Commercial Power Converters



250V/ 0.1A SiC Schottky Diode

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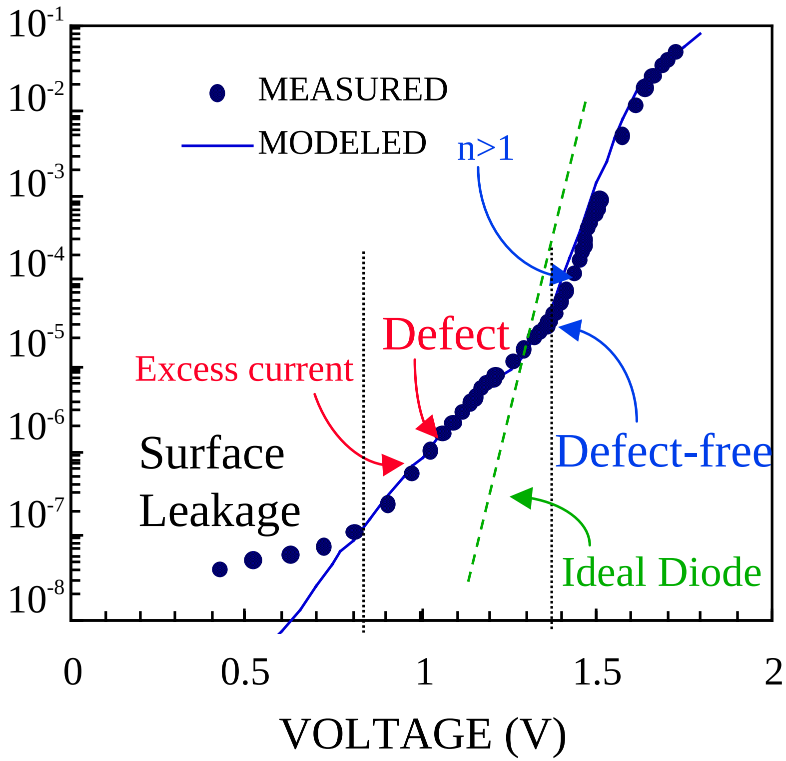
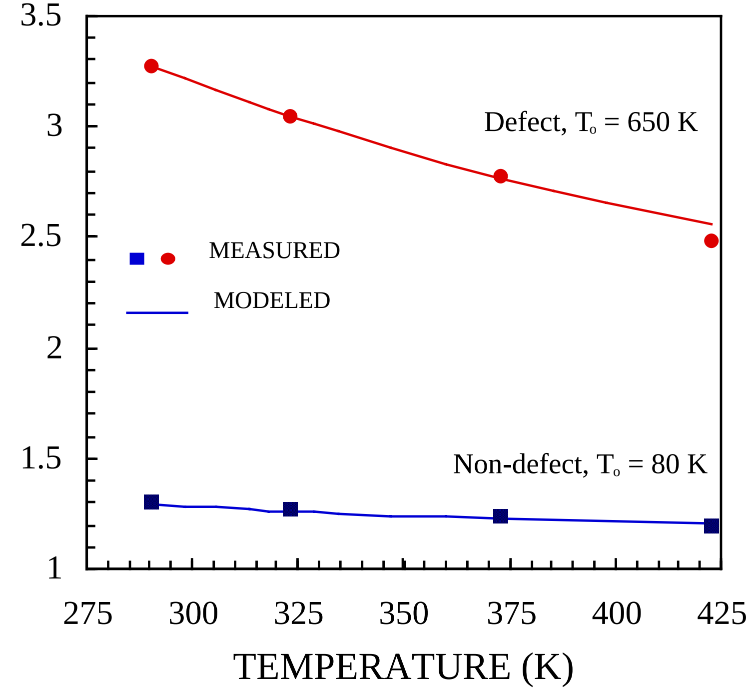
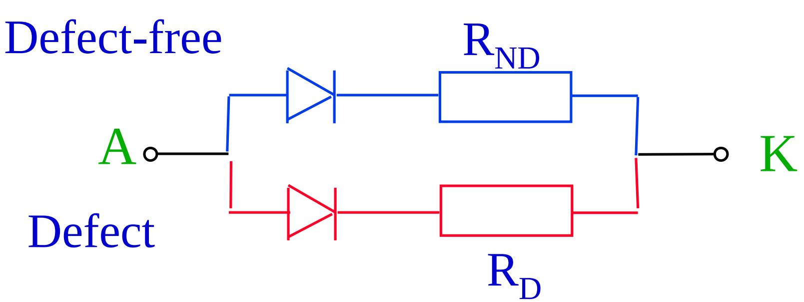
Static Characteristics



Ideality Factor





- Anomalies in forward conduction
- Material parameters vary at defect sites
- Ideality factor (n) represents quality of the diode
- A good diode has n ~1

Forward I-V Characteristics

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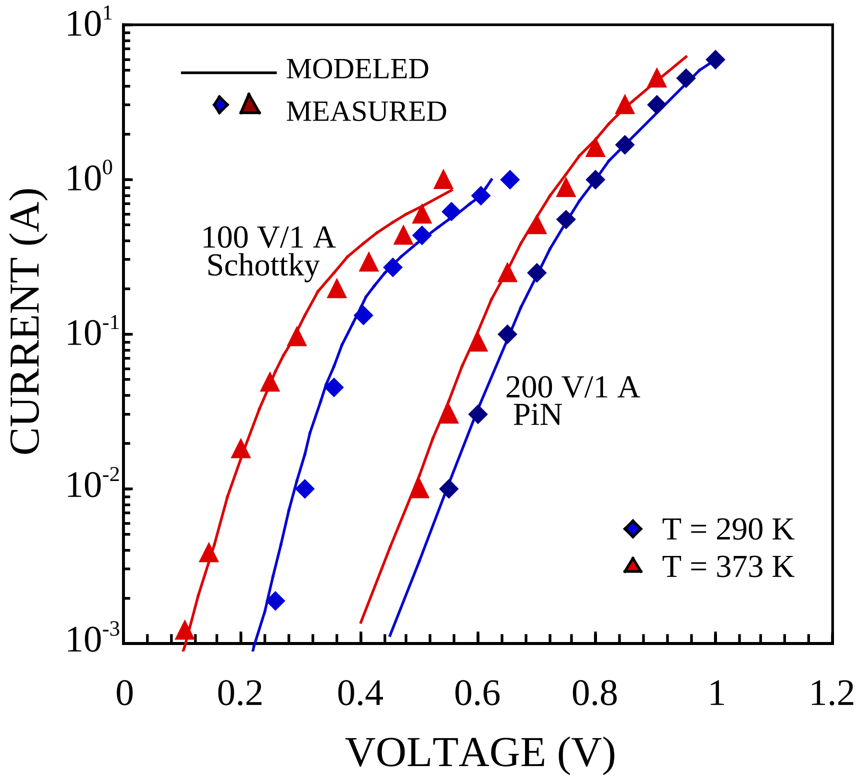
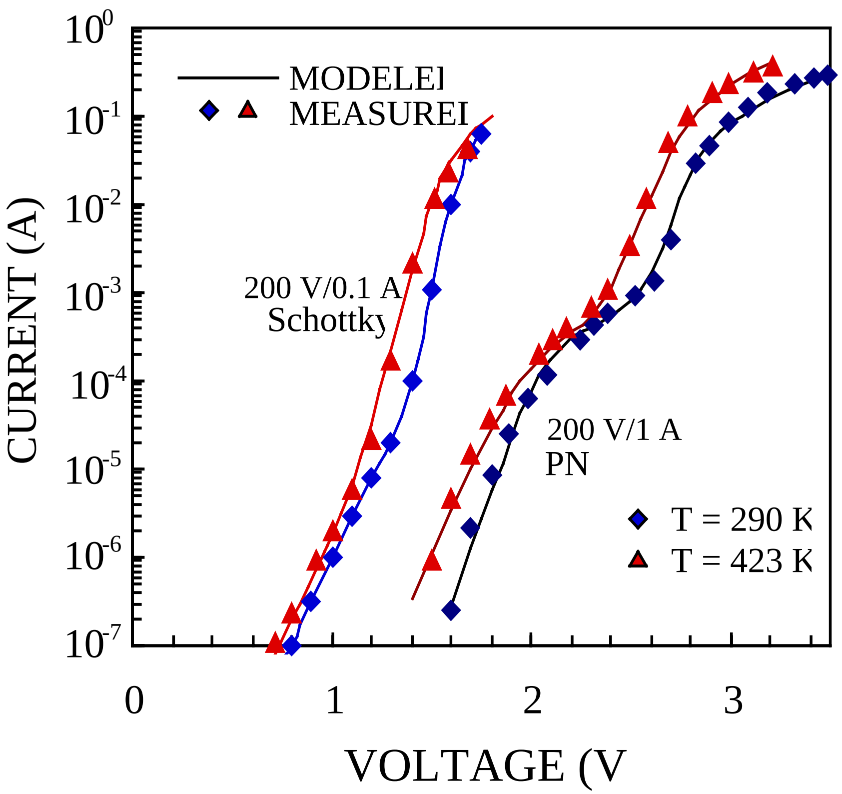
Si Diode



4H-SiC Diode



Si diodes have much lower on-state voltage than SiC diodes

Defect-induced excess current in SiC Schottky and PN diodes at low forward bias

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Reverse Recovery Test Circuit

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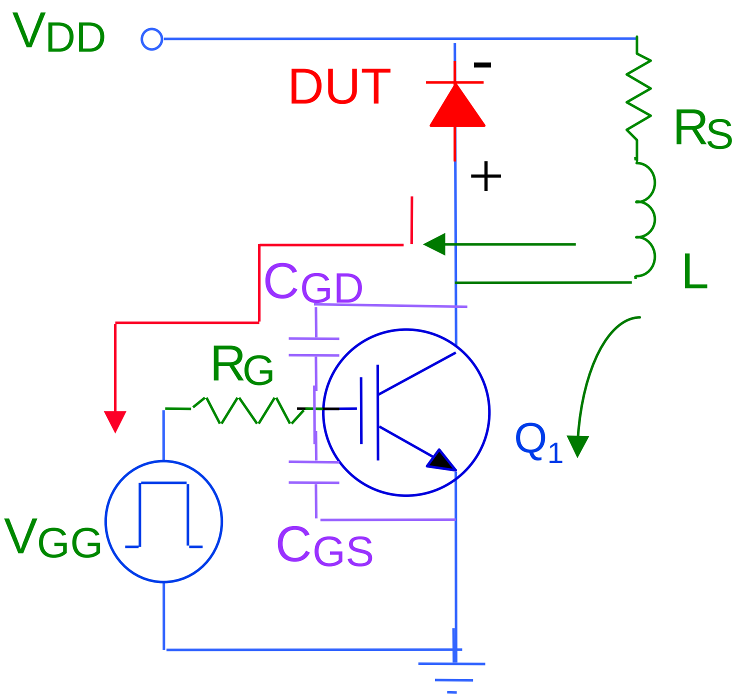
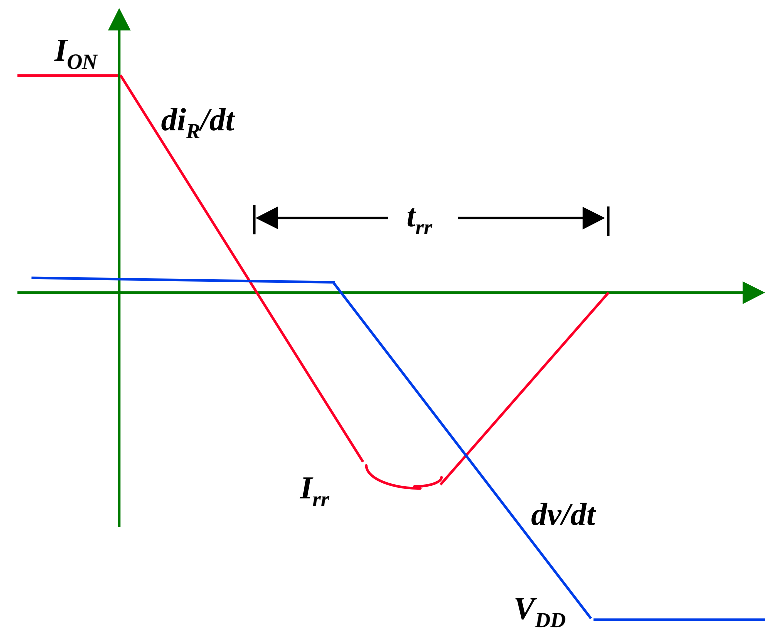
Test Circuit



- Forward current adjusted with pulse width of Q_1 gate pulse
- Gate pulse is applied to Q1 to intiate reverse recovery of diode
- Turn-off dI/dt is controlled by R_G
- Reverse recovery performance under various conditions of V_{DD}, I_{ON}, di_R/dt

Reverse Recovery



I_{ON}: Forward Current
di_R/dt: Turn-off di/dt
dv/dt: Recovery dv/dt
I_{rr} : Peak Reverse Recovery Current
t_{rr} : Reverse Recovery Time

Reverse Recovery Performance

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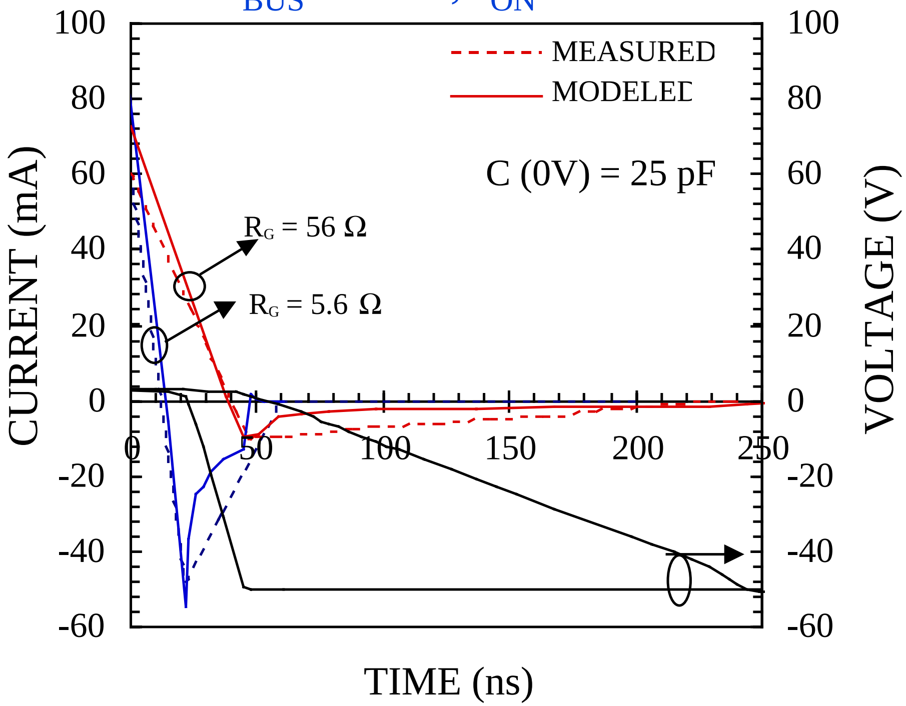
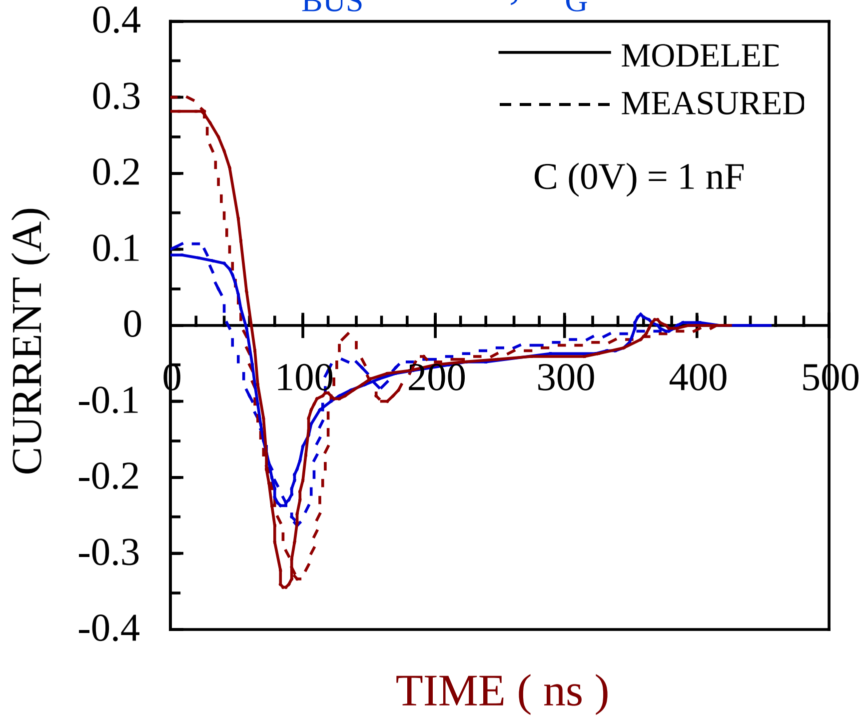
200 V/0.1 A
4H-SiC Schottky Diode
V_{BUS} = 50 V, I_{ON} = 60 mA



200 V/1 A
4H-SiC PN Diode
V_{BUS} = 40 V, R_G = 10 Ω



Tail in turn-off current appears because of junction capacitance
Schottky diode reverse recovery independent of temperature
PN diode reverse recovery weakly dependent on on-state current

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DC-DC Buck Converter for Diode Testing

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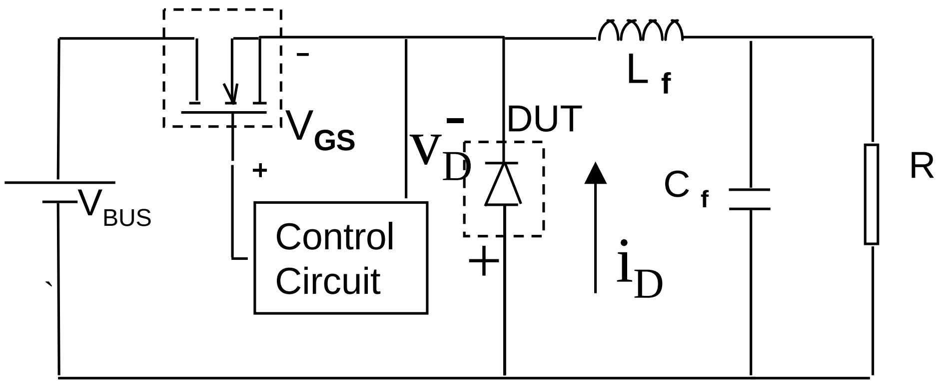
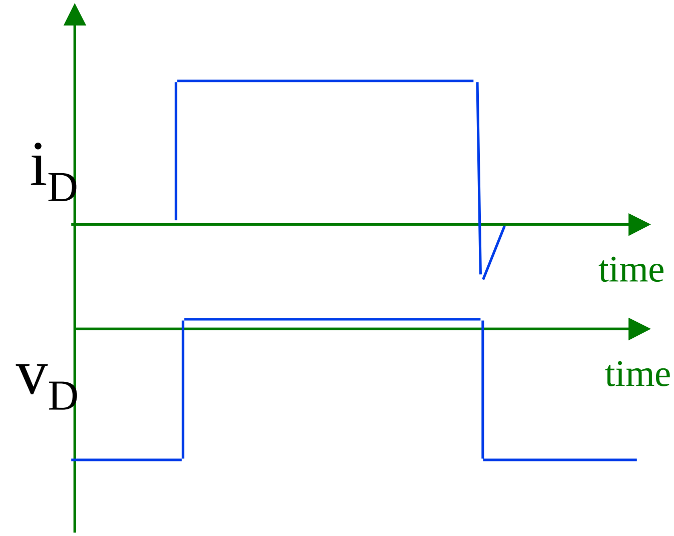
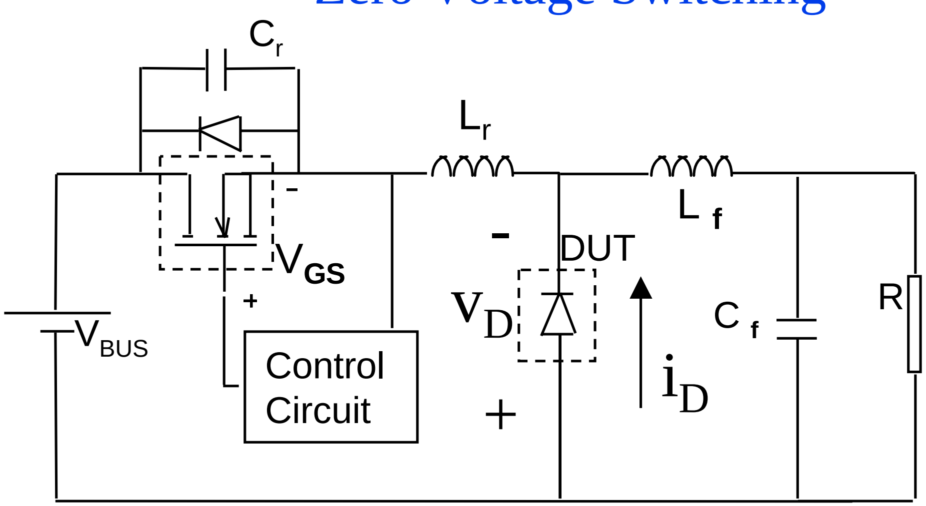
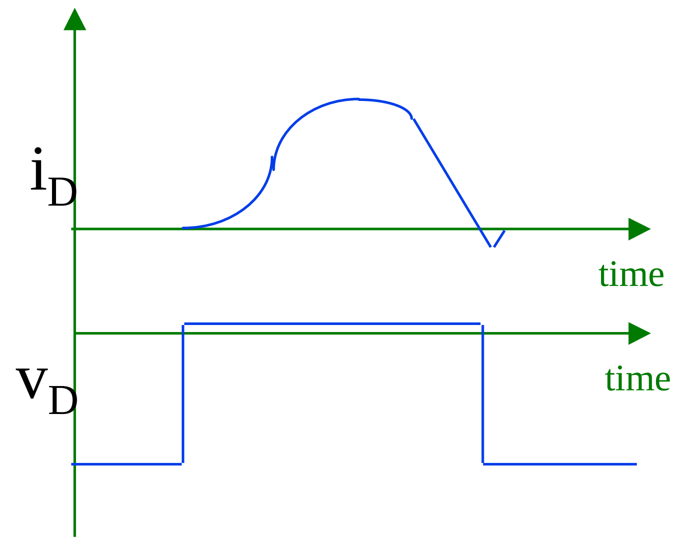
Hard Switching





Zero Voltage Switching





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DC-DC Buck Converter Performance

SiC Schottky, SiC PN and Si PiN diodes

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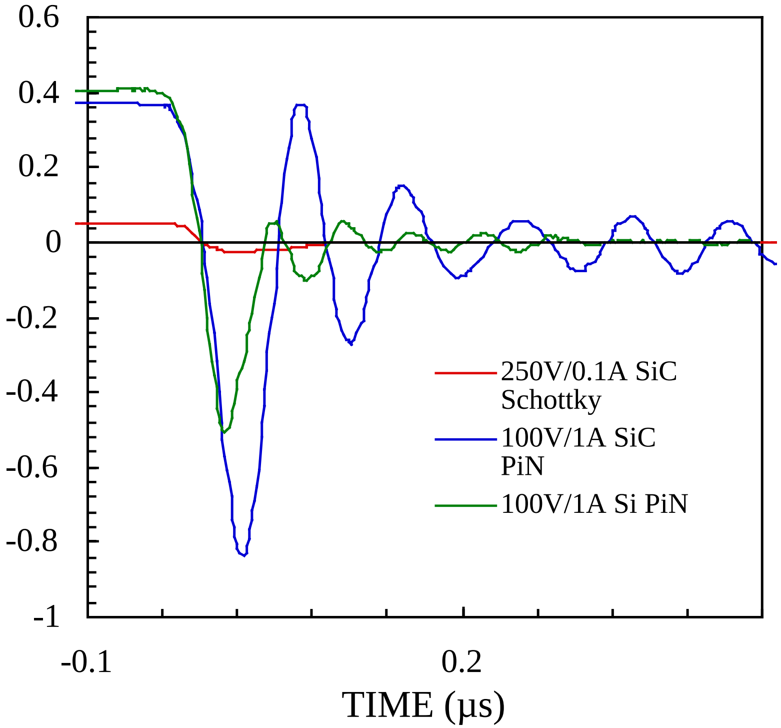
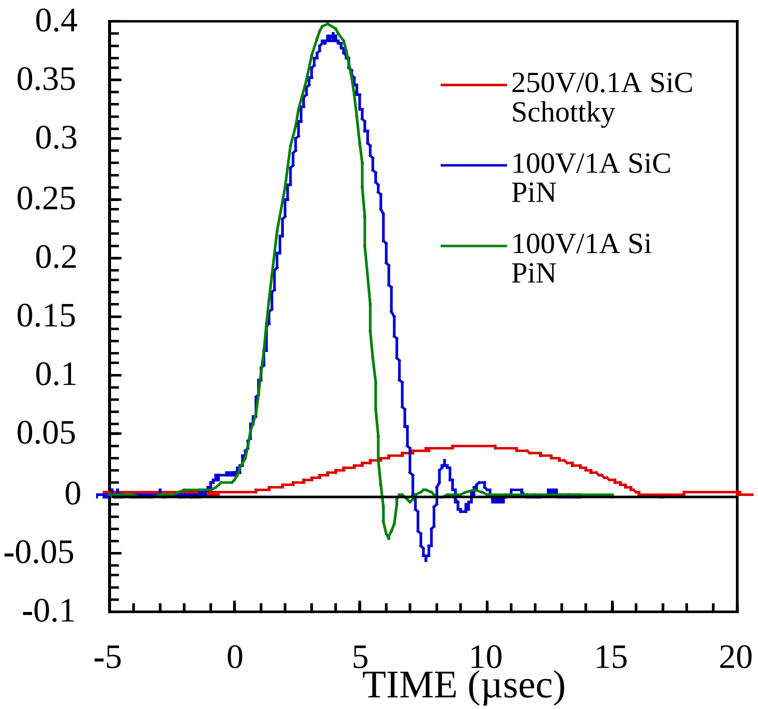
Hard Switching



Zero Voltage Switching



- Comparable switching performance of low-voltage SiC and Si PiN Diodes
- Negligible switching transient in zero voltage switching configuration
- Low voltage SiC devices only offer advantage of high-temperature operation

Hard-Switching Buck Converter Performance

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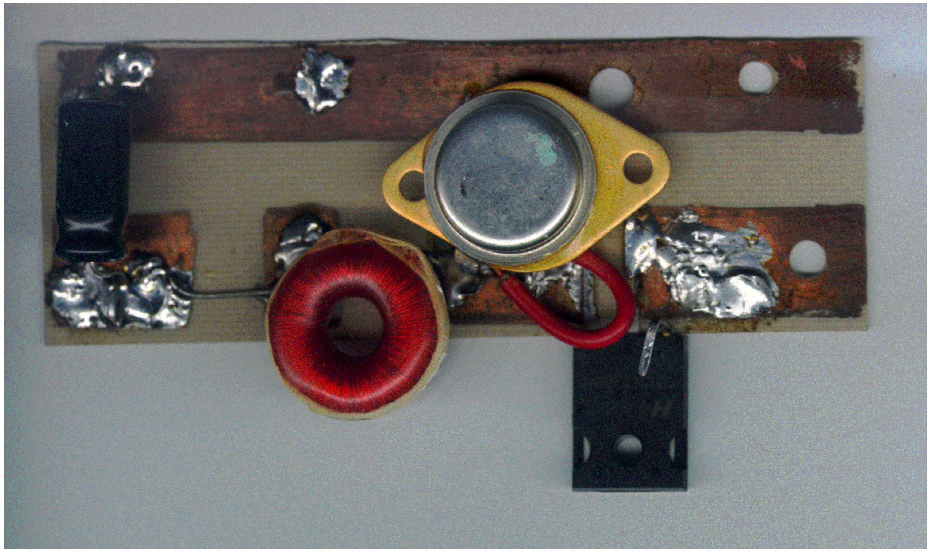

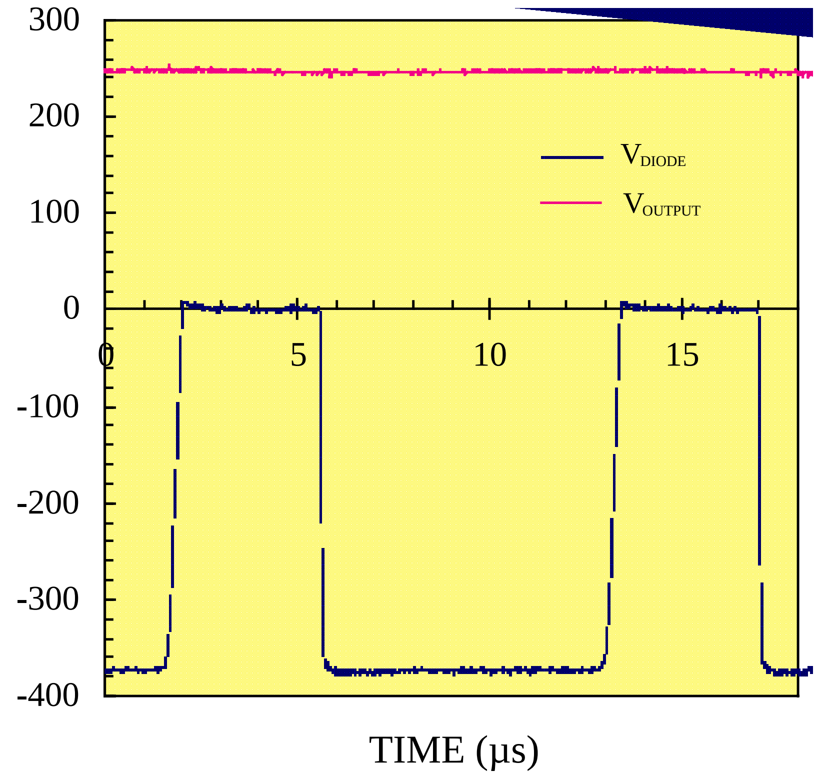

Converter Parameters

Switch : 600 V/ 5 A Si MOSFET
Inductor : 5 mH
Capacitor : 1 μF
Frequency : 90 kHz
I/O Voltage : 400 V/ 250 V
Output Power : 150 W

Si diode converter failed at 90 W, 30 kHz, 290 K

Simulation of Diode Performance
Hard-Switching of PiN Diodes

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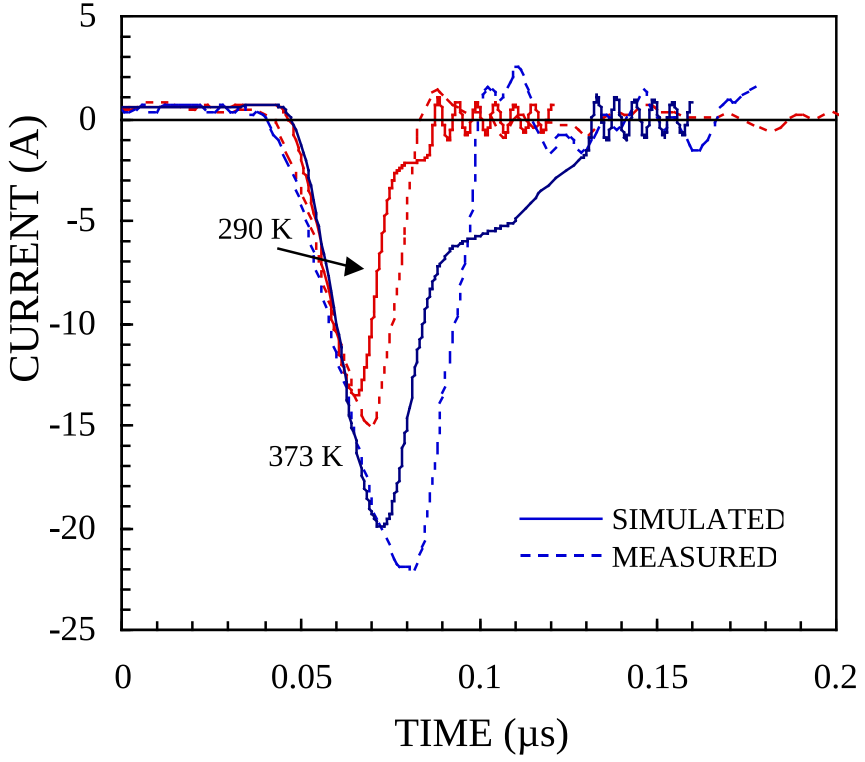
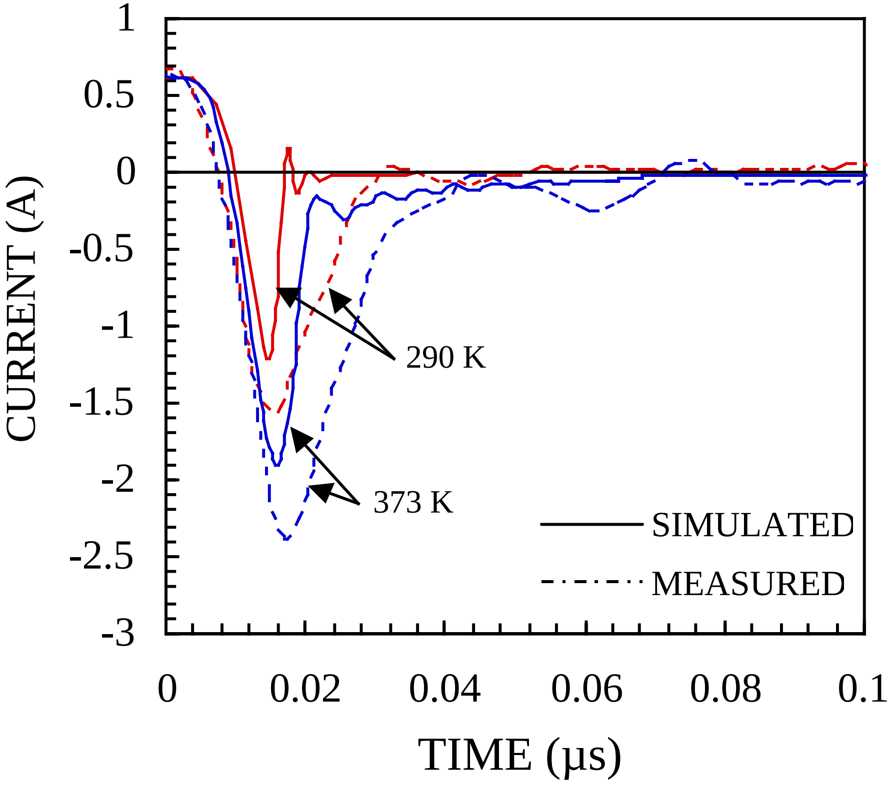
1.5 kV/10 A Si



3 kV/1 A 4H-SiC



Reasonable match between static and switching simulations and measurement
4H-SiC material parameters from recent published reports

ZVS Buck Converter Performance
PiN Diodes

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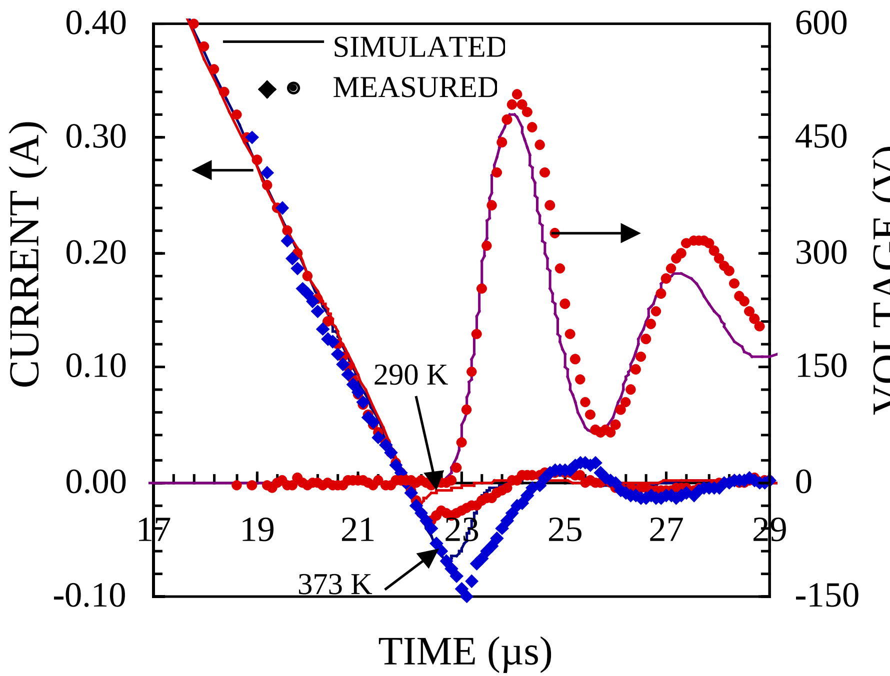
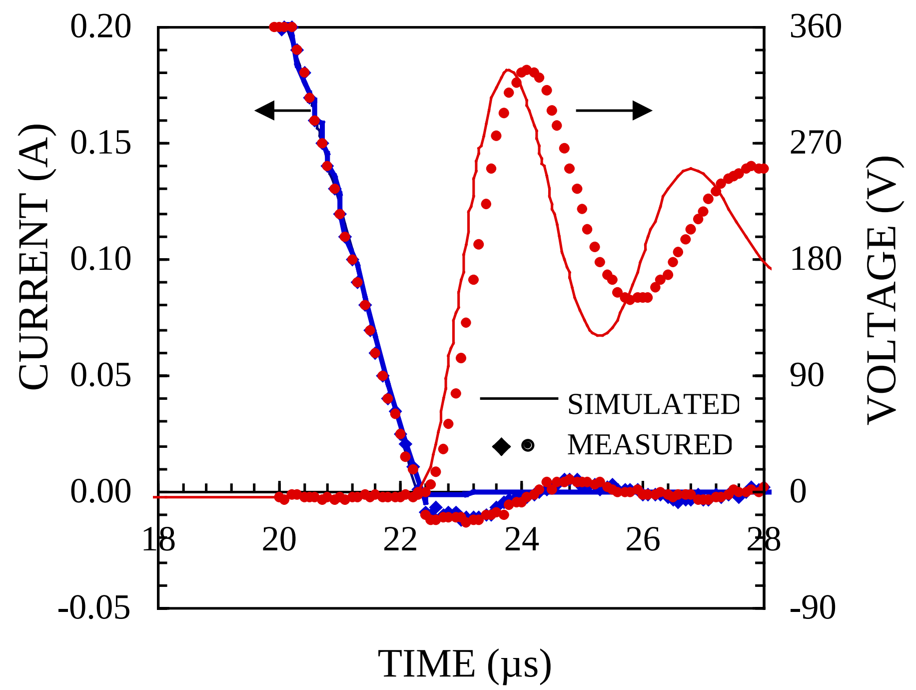
V_{BUS} = 200 V, I_{MAX} = 0.6 A

1.5 kV/10 A Si



3 kV/1 A 4H-SiC



Reasonable match between static and switching simulations and measurement
4H-SiC material parameters from recent published reports

Comparison of Si and 4H-SiC High-Voltage PiN Diodes

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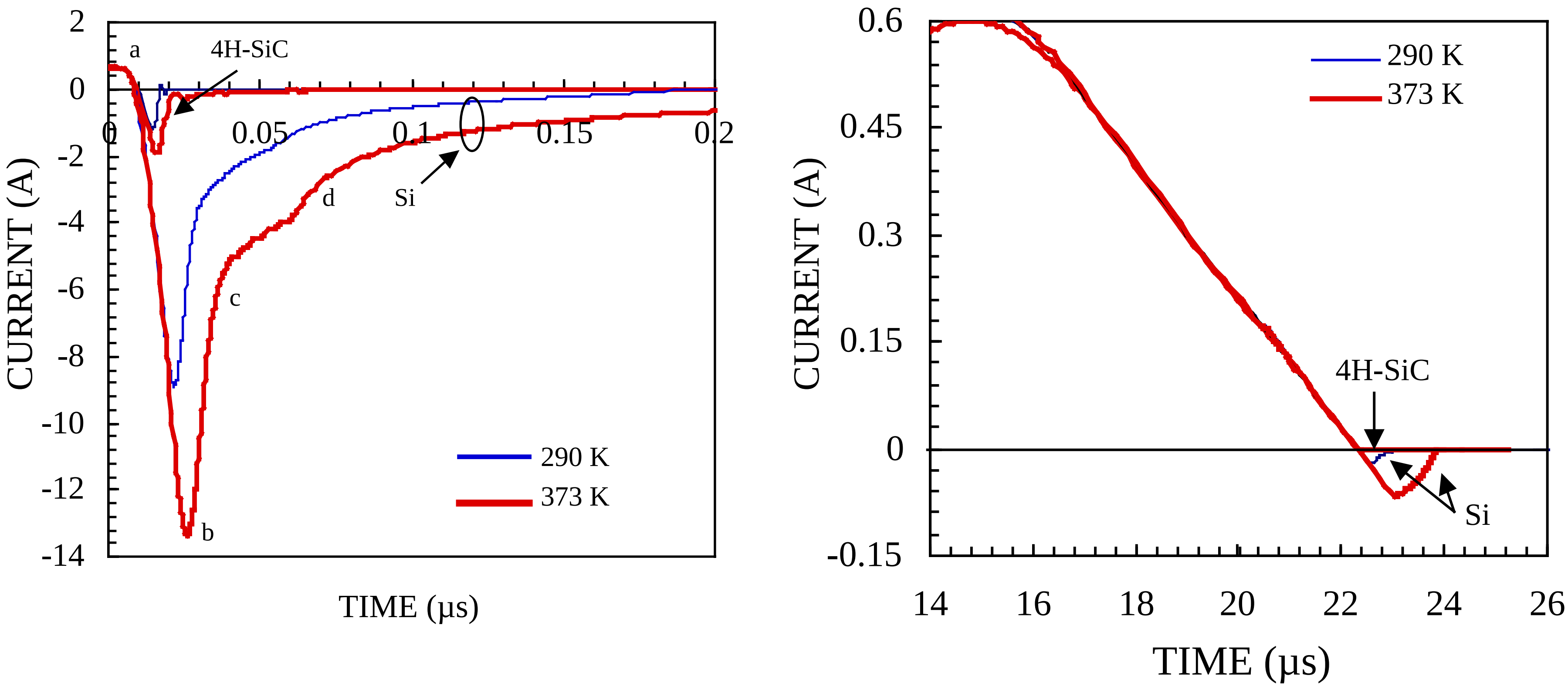
Hard-Switching

V_{BUS} = 300 V, J_F = 100 A/cm^2

Soft-Switching

V_{BUS} = 200 V, J_F = 100 A/cm^2



SiC has negligible reverse recovery compared to Si under identical switching conditions

Considerable performance improvement in Si diode with soft-switching (lower *di/dt*)

Charge Decay During Reverse Recovery (PiN Diode 2-D Simulations)

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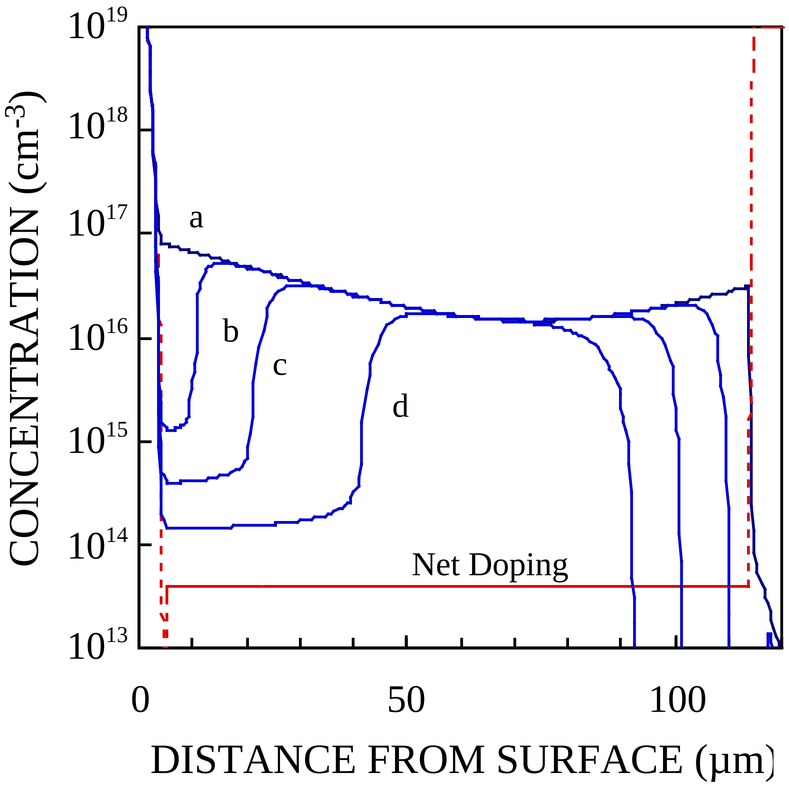
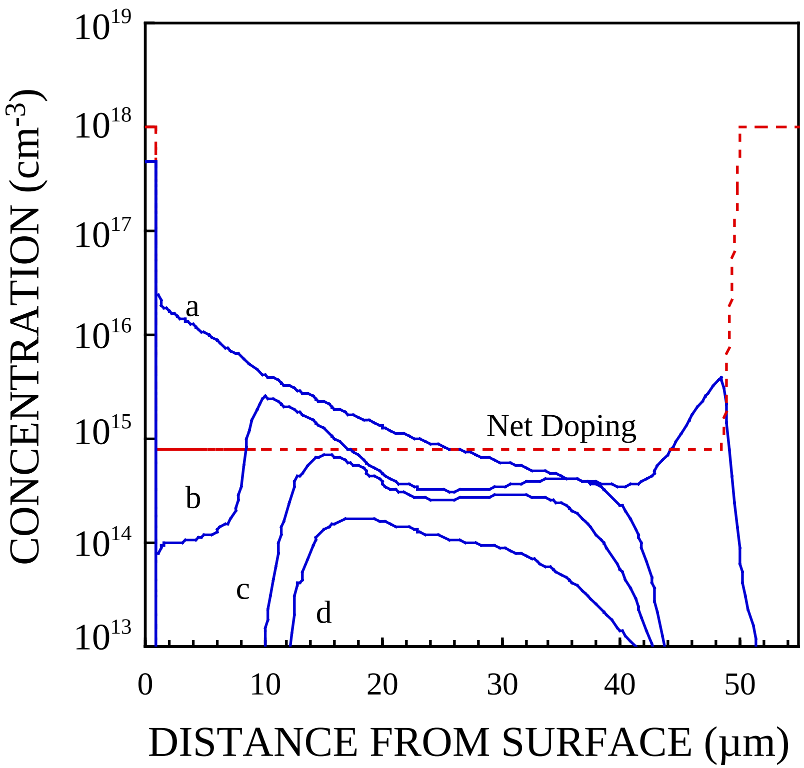
1.5 kV/1 A Si



3 kV/1 A 4H-SiC



Si diode has very high excess charge in drift region

Rapid charge decay in SiC diode because of low carrier lifetime

Current tail because of excess charge trapped in quasi-neutral drift region

Simulated PiN Diode Buck Converter Performance Trend

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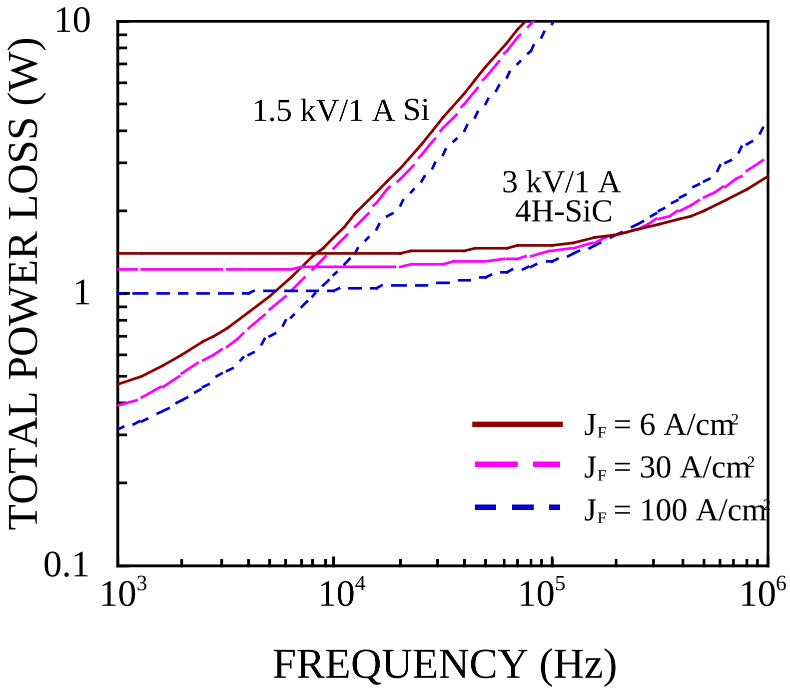
300 V/150 V, 90 W, 373 K

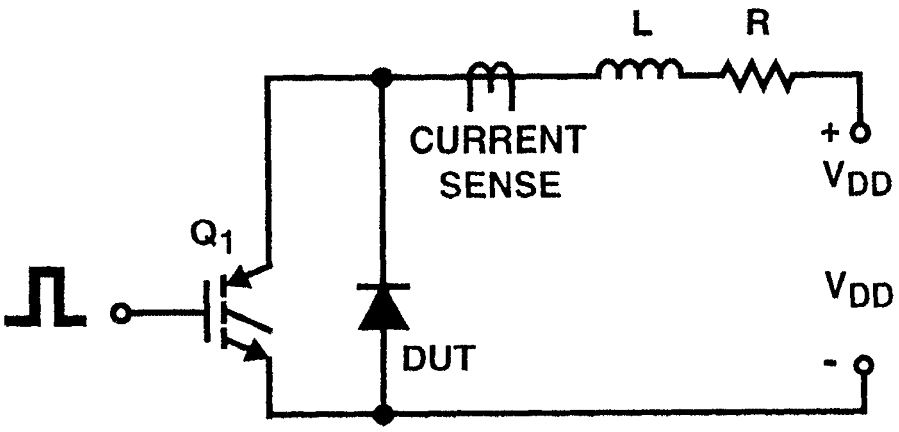


$$P_D = DV_{ON} I_{ON} + E_{sw} f_{sw}$$

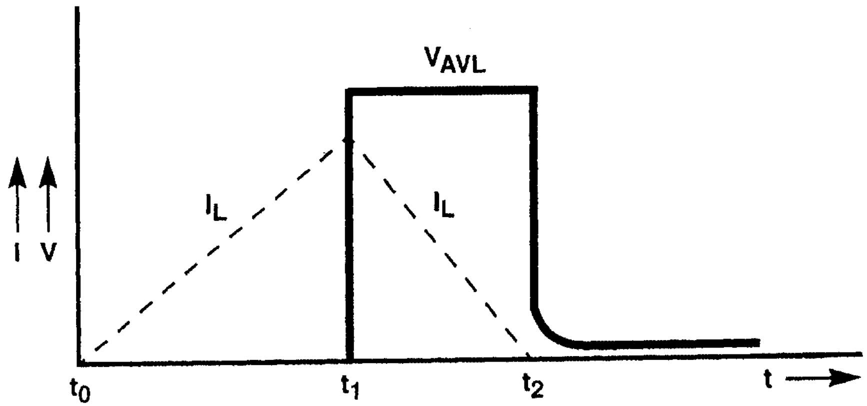
- Total power loss in Si diode is very sensitive to switching frequency
- Frequency dependence of SiC diode above 300 kHz
- Total loss in SiC diode dominated by conduction loss
- Switching loss in Si diode appears because of excess charge removal
- Switching loss in SiC diode appears because of junction capacitance

Reliability Testing of Diodes

TEST CIRCUIT



TYPICAL WAVEFORMS



- Performance evaluation was conducted at voltage and current levels much lower than rated values
- Fragile SiC devices

- Assessment of device reliability is crucial
- Dynamic stress testing to determine avalanche rating of SiC diodes

High-Density SiC Power Converters

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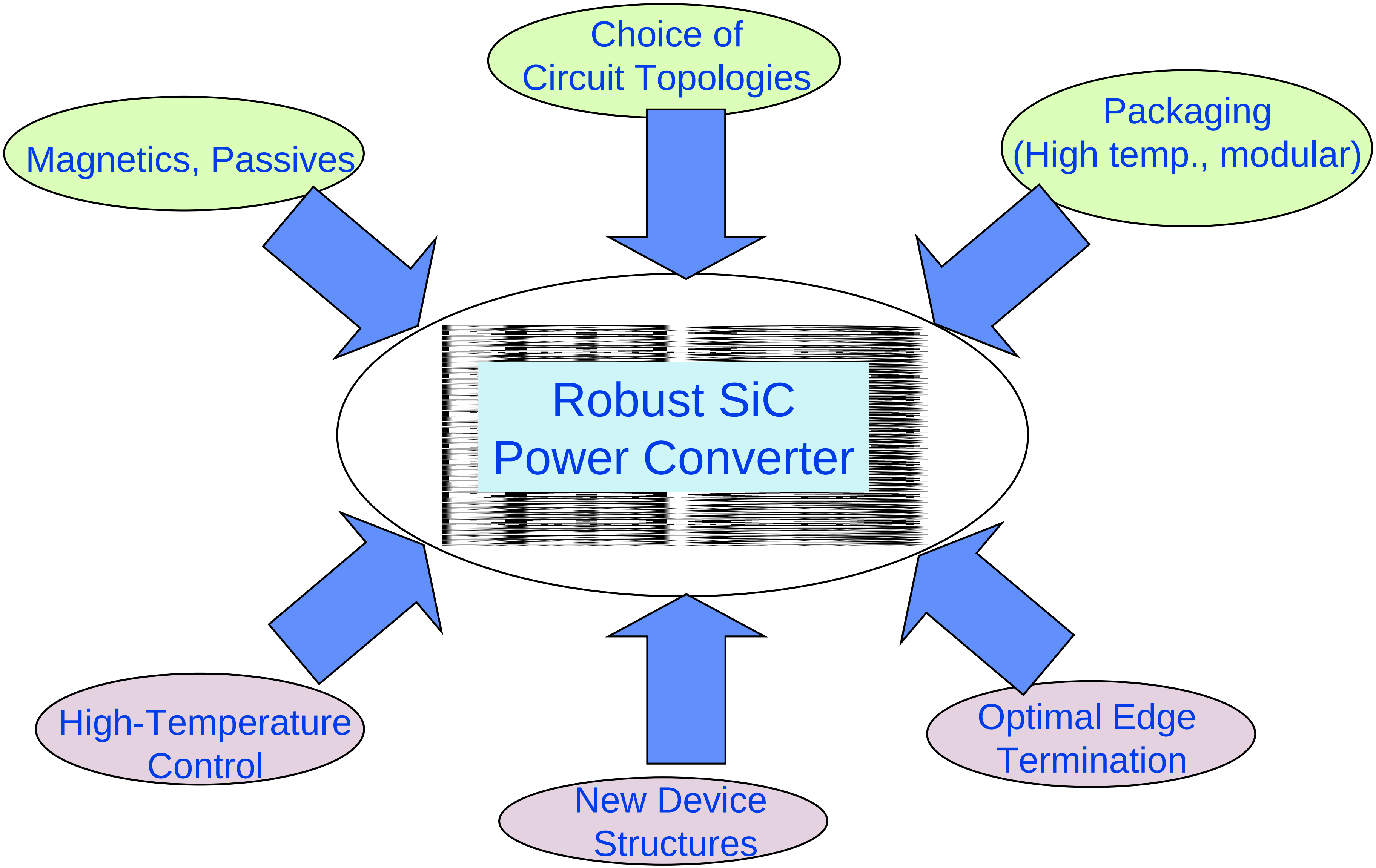

NASA Schottky Diodes

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- Performance evaluation of 4H-SiC schottky diodes was conducted
- Comparative study of diodes with different perimeters and areas was conducted
- Tests were conducted to evaluate the dv/dt withstanding capability of the diodes
- 5 identical samples of each device were tested for consistency in results
- All devices were rated at I kV

Breakdown Performance

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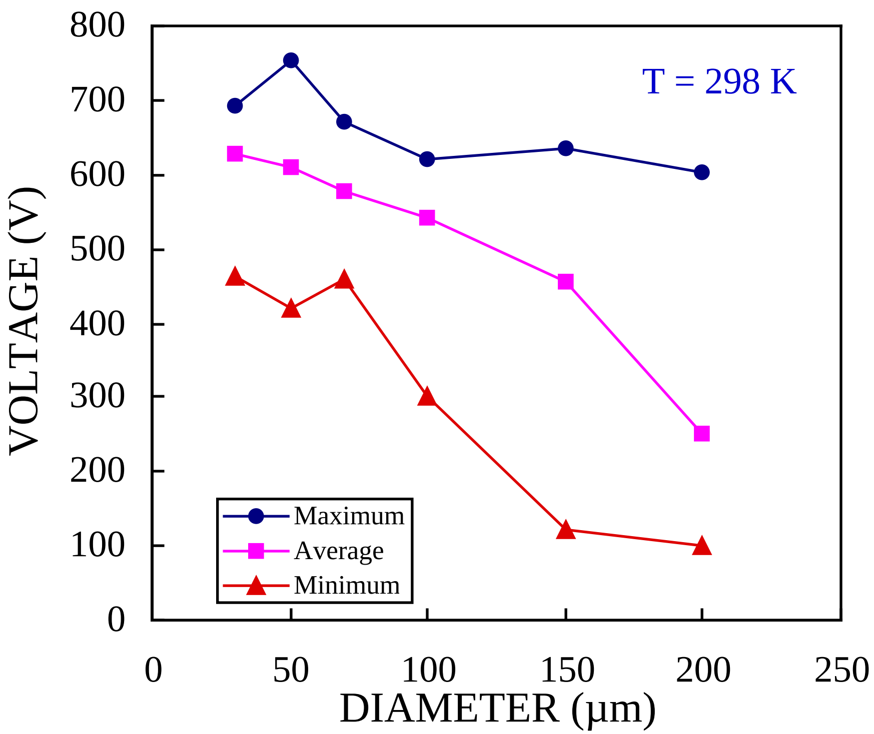
MEASURED RESULTS



- Strong area dependence of breakdown voltage was observed
- Highest breakdown voltage of 750 V was measured on a 50 µm device
- Lowest breakdown voltage of 100 V was measured on a 200 µm device
- High temperature breakdown measurements were not performed

Forward I-V Characteristics

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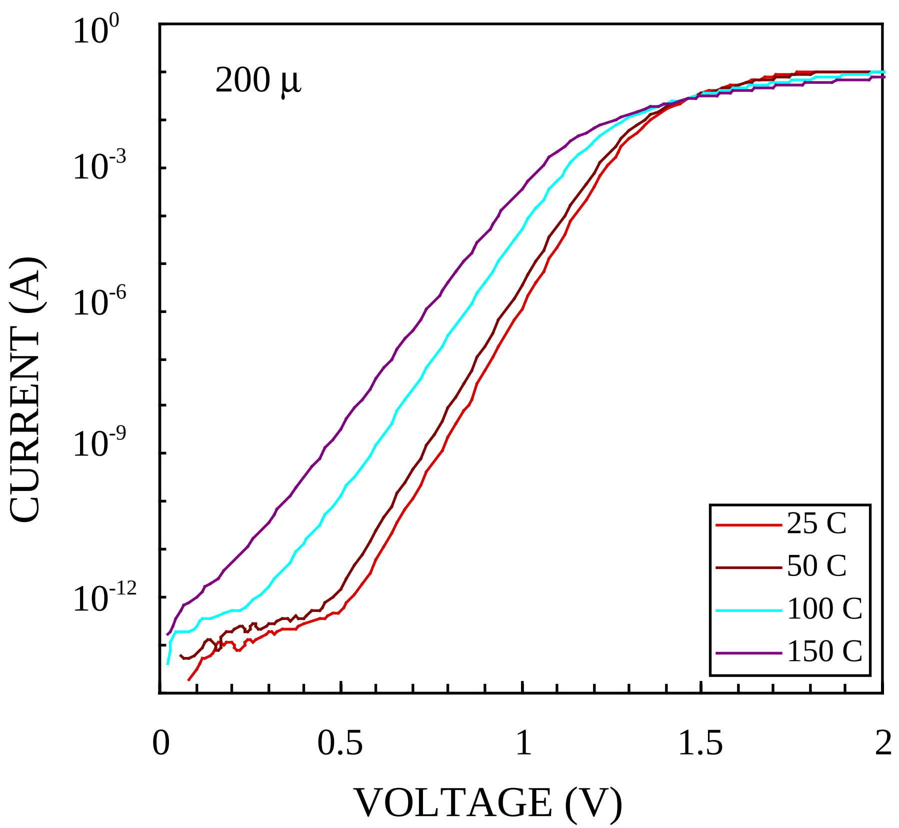
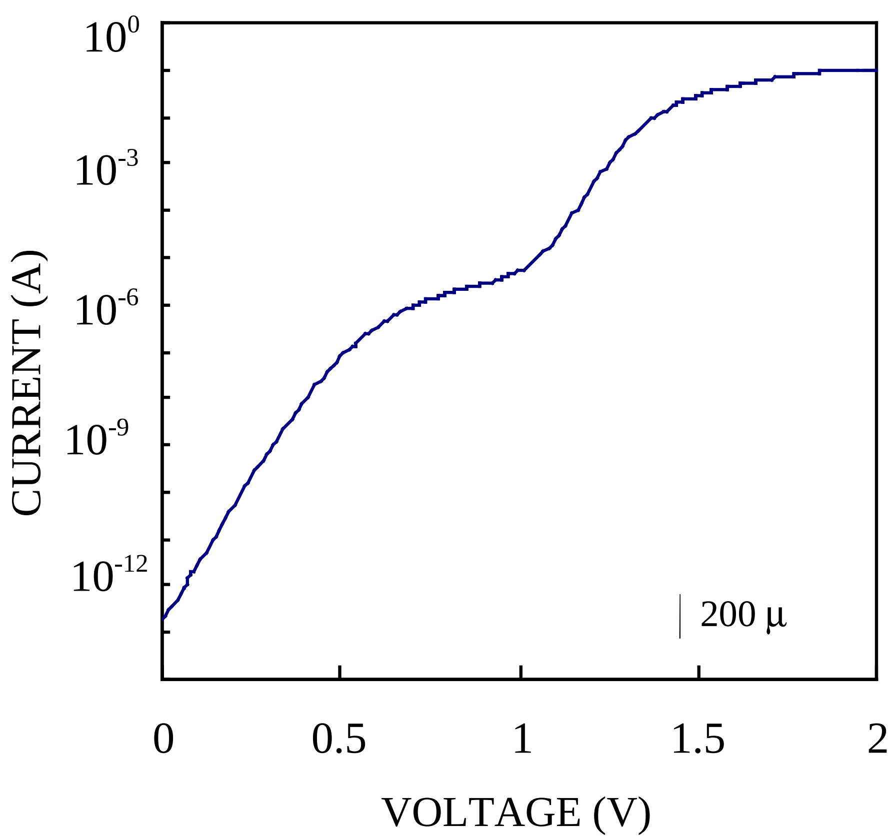
NON - DEFECTIVE DIODE I-V



DEFECTIVE DIODE I-V



- Leakage current increases with temperature
- Defective diode current starts rising rapidly at very low bias voltages

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Forward J-V Characteristics

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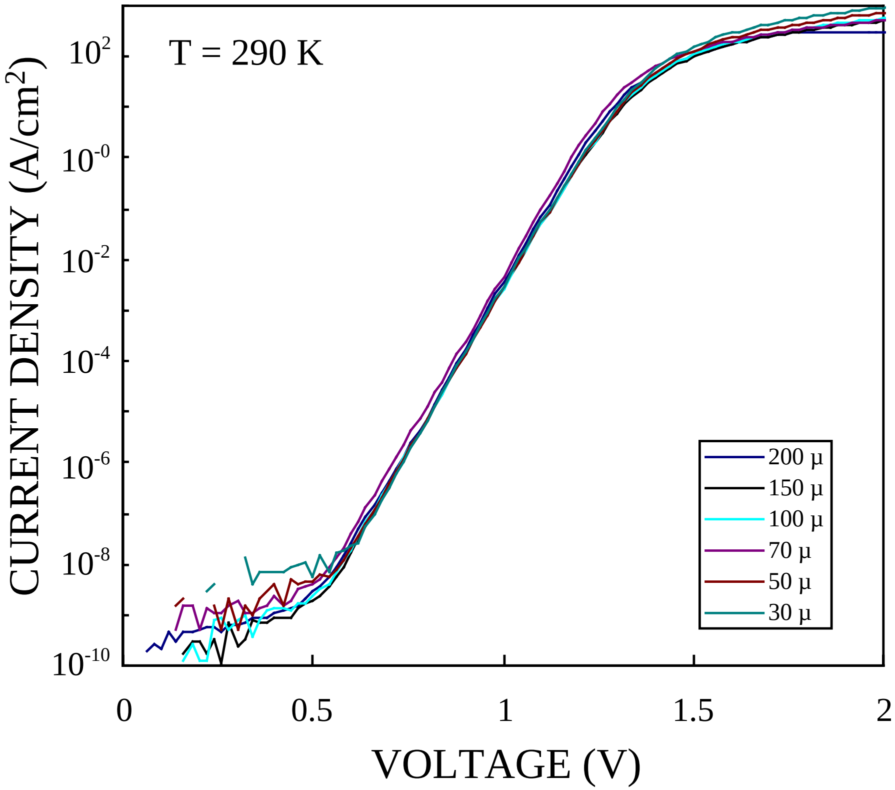
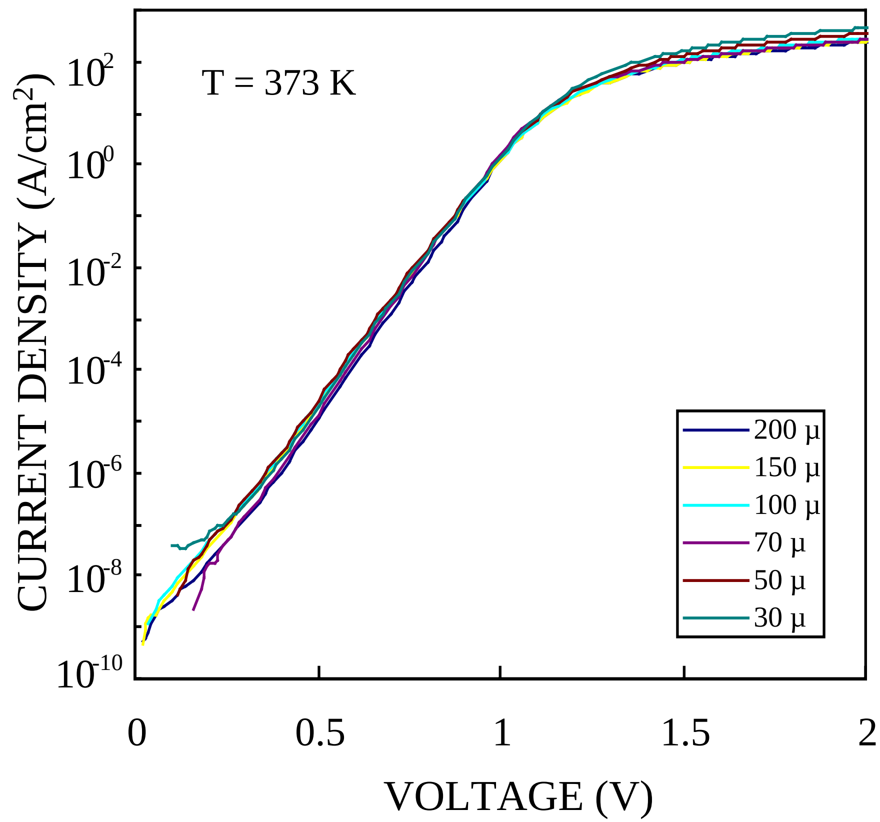
MEASURED WAVEFORMS





- Influence of perimeter on leakage current density is negligible

Perimeter/Area Dependence

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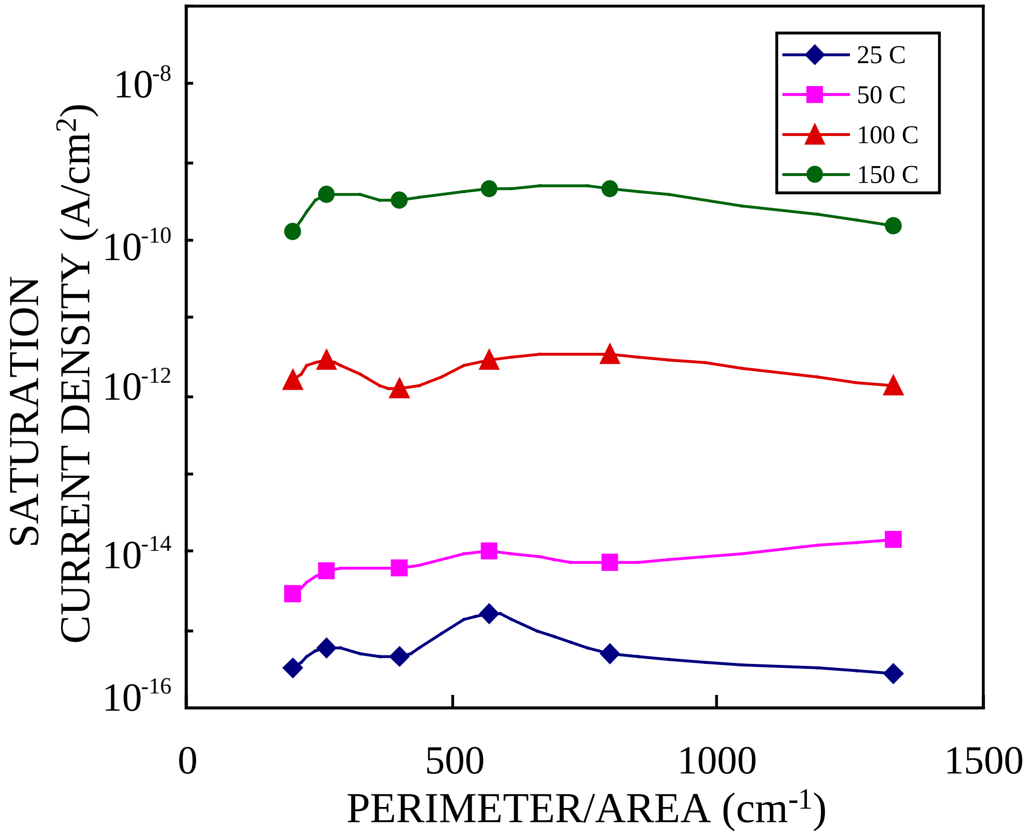

- Saturation current densities were extracted from the J-V characteristics
- Saturation current density is independent of P/A ratio
- No perimeter recombination current along the periphery because of absence of a junction

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Ideality Factor Extraction

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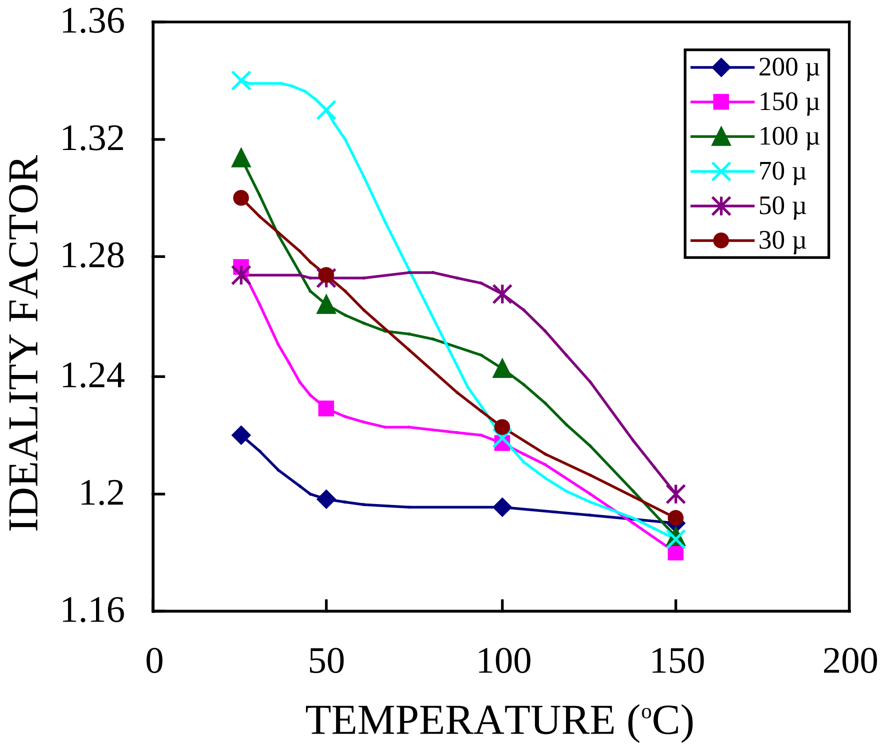

- Ideality factor was extracted from forward I-V characteristics

$$n = \frac{1}{\frac{\partial(\ln I_F)}{\partial V_F} V_T}$$

- Room temperature ideality factor ranged from 1.22 - 1.33

- Ideality factor decreases with temperature

- Thermionic emission current contribution is more at higher temperatures.

- Therefore the ideality factor approaches unity

Reliability Testing of Diodes

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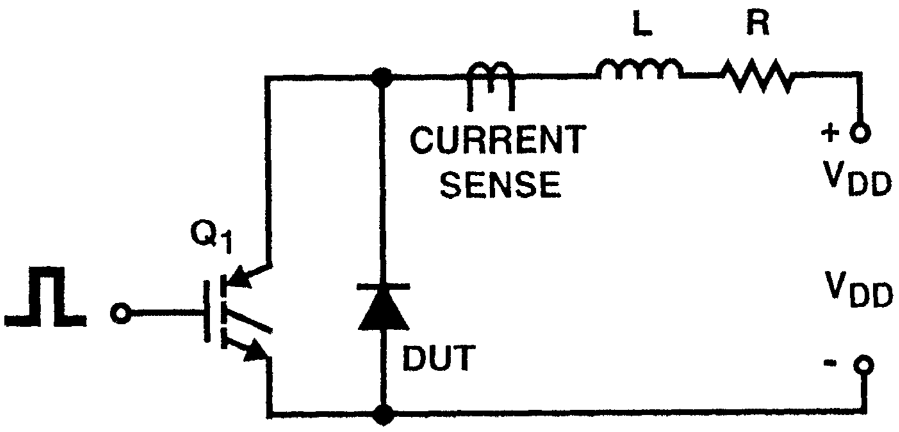
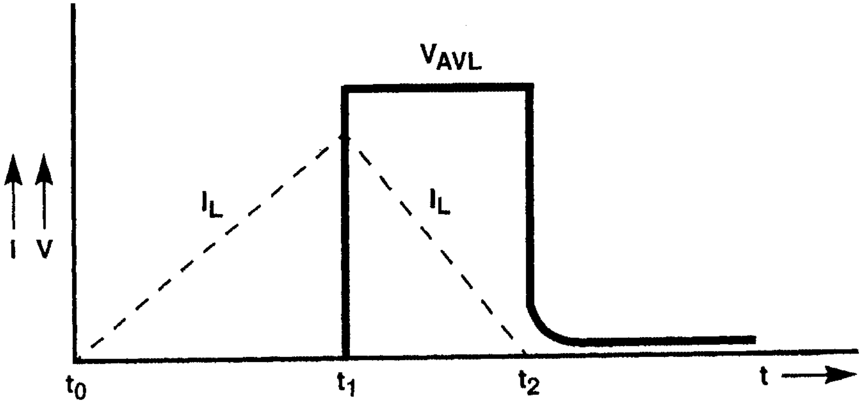
TEST CIRCUIT



TYPICAL WAVEFORMS



- Performance evaluation was conducted at voltage and current levels much lower than rated values
- Fragile SiC devices

- Assessment of device reliability is crucial
- Dynamic stress testing to determine dv/dt rating of SiC diodes

dv/dt Characterization

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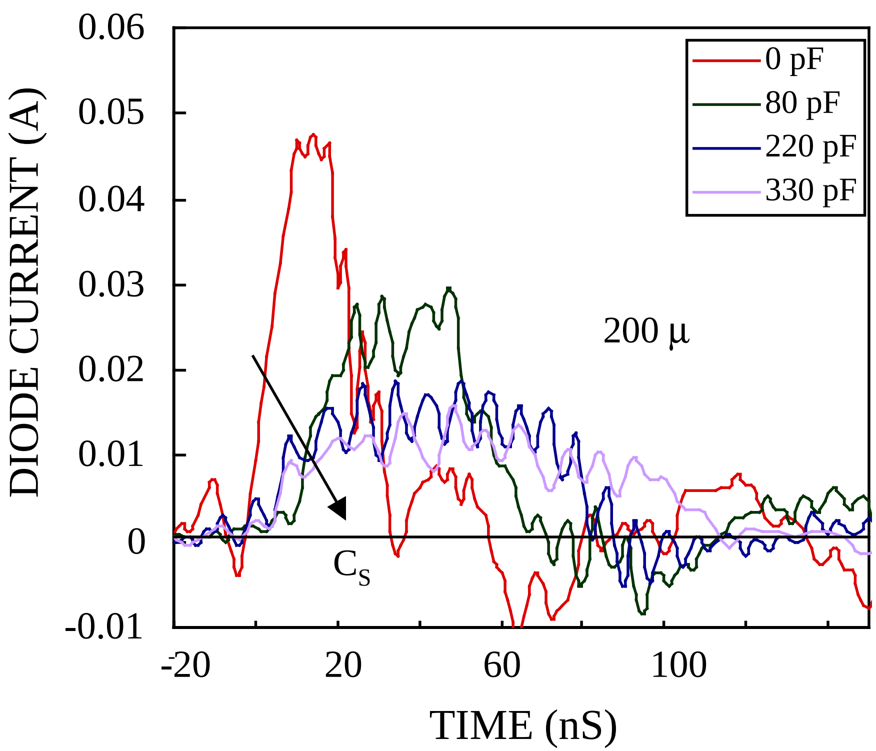
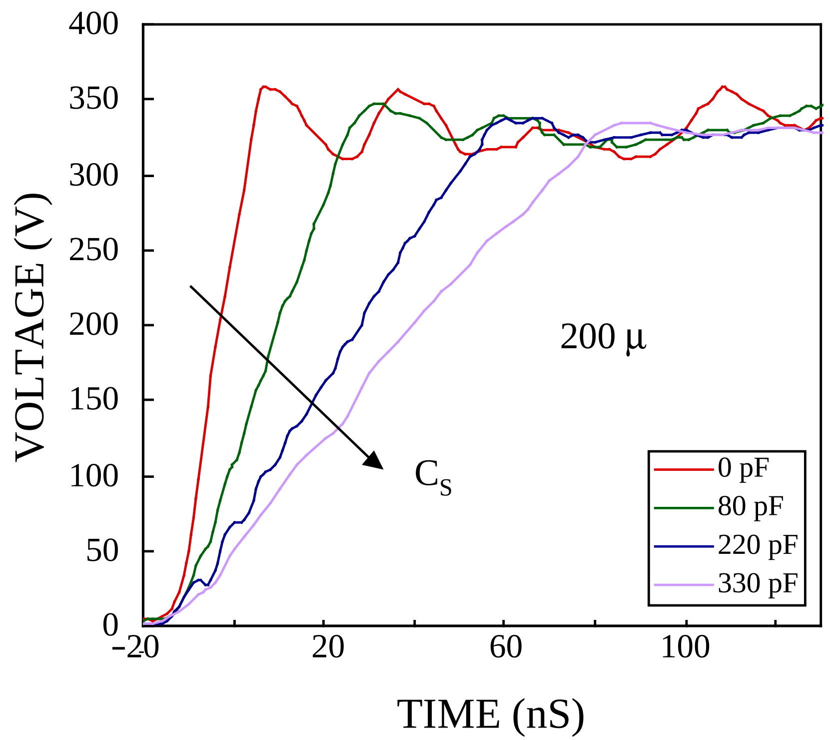
DIODE WAVEFORMS





- Diode current increased at higher dv/dt
- dv/dt varied from 4V/ns to 30 V/ns
- With a 250 V switch the DUT survived the highest applied dv/dt
- With a 500 V switch the device failed even for the lowest dv/dt
- Failure was voltage dependent rather than dv/dt

SiC Diodes
for
SMPS applications

Forward I-V Characteristics

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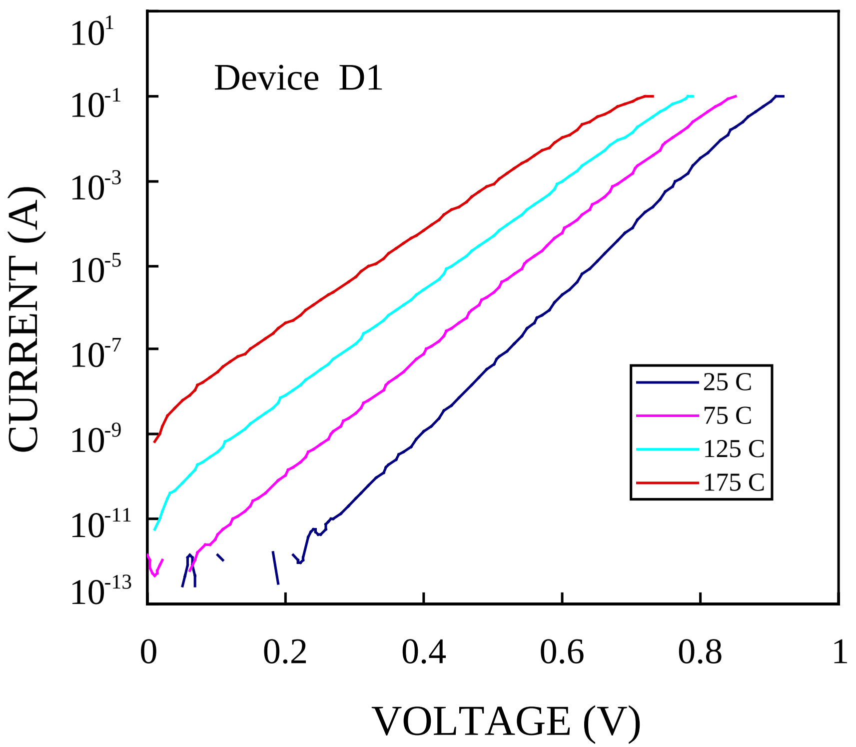
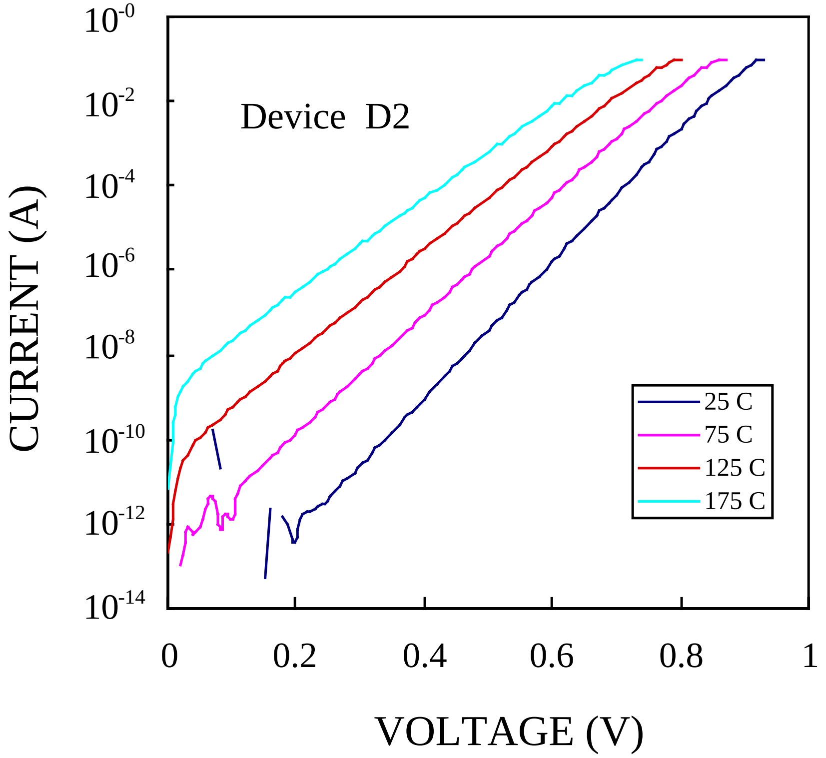
MEASURED WAVEFORMS

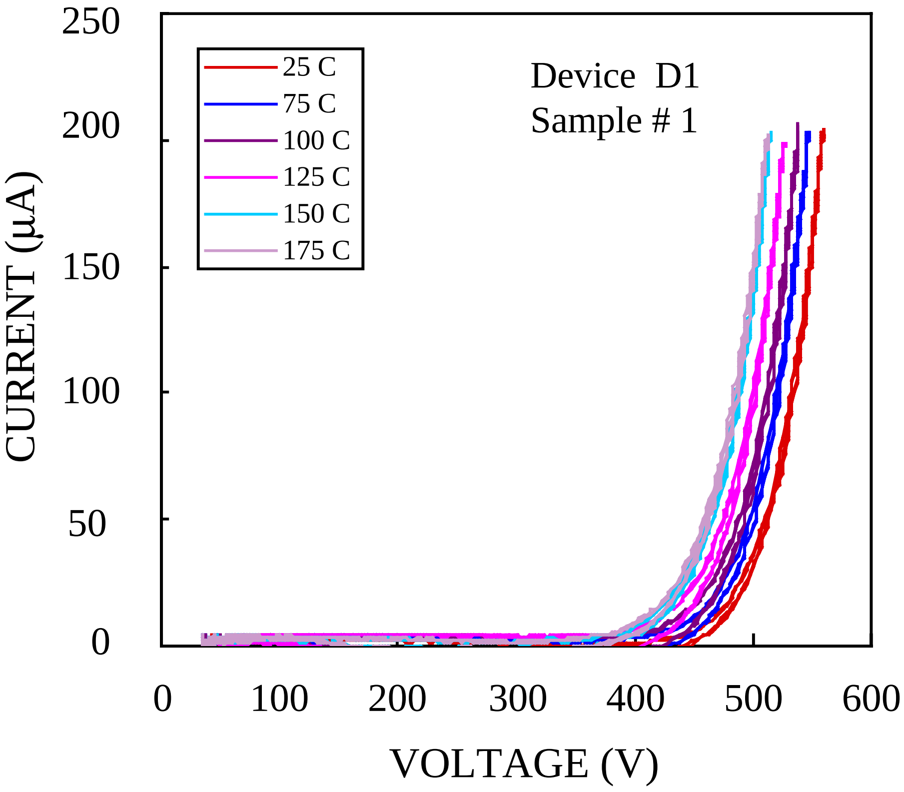


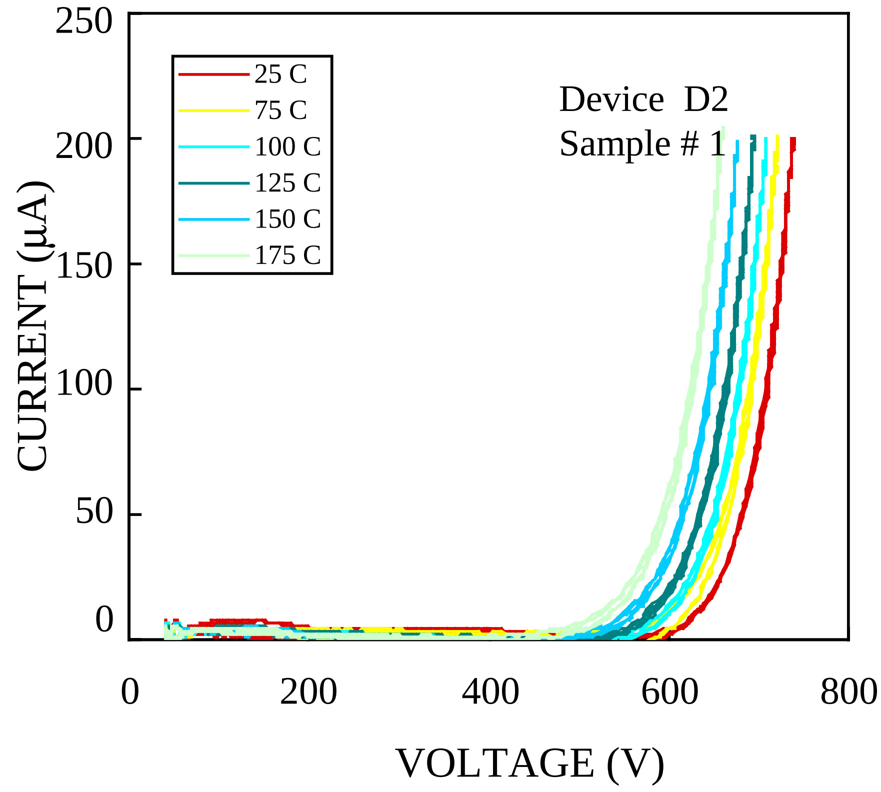


- 5 samples of each device were tested for consistency
- Leakage current increases with temperature

Breakdown Performance

MEASURED WAVEFORMS





- Breakdown voltage decreases with increase in temperature

Breakdown Performance

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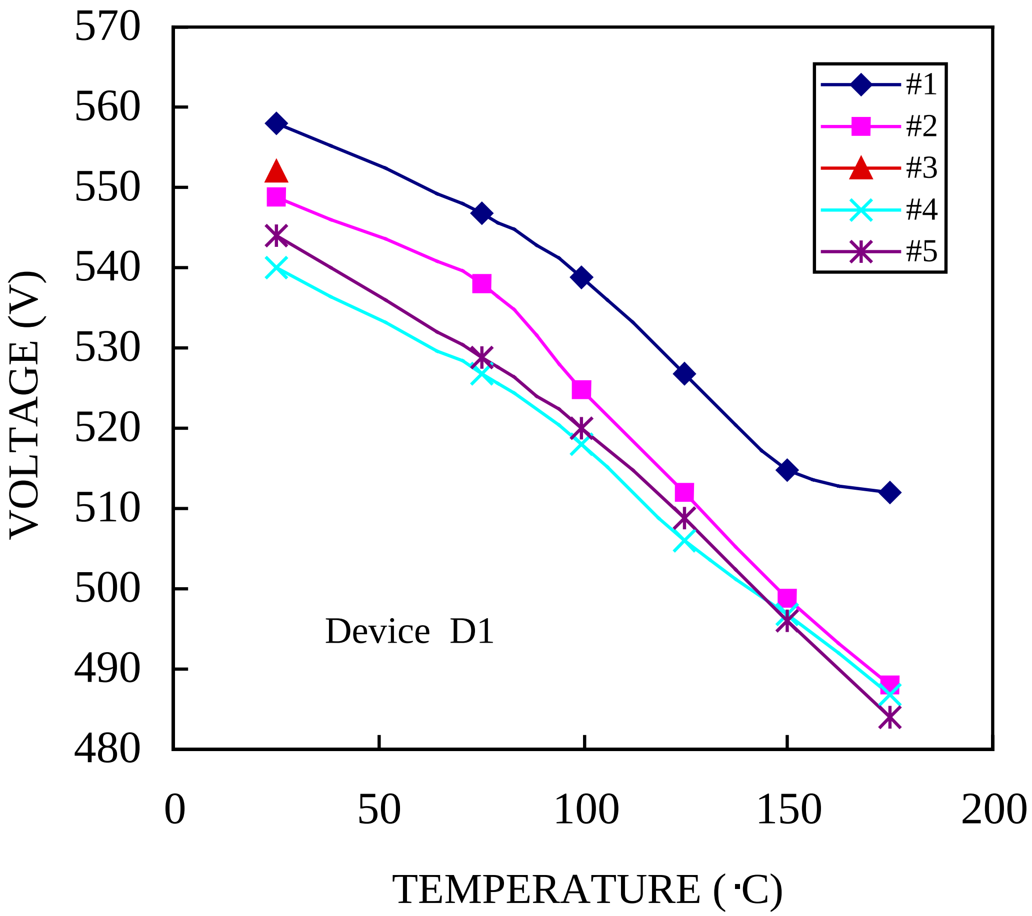

- 5 samples of device D1 were characterized
- Sample # 2 failed during testing
- For every **1·C** rise in temperature the voltage drops by **0.5** V approximately

Breakdown Performance

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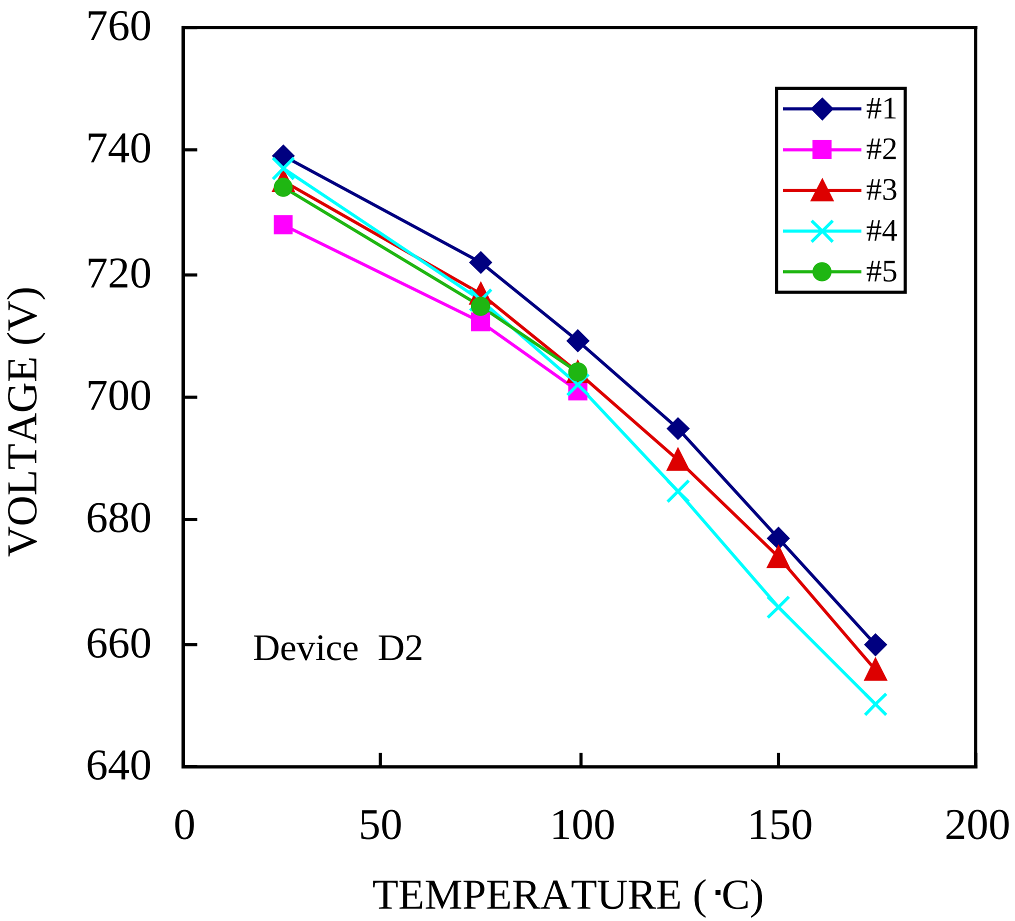

- 5 samples of device D2 were characterized.
- Sample # 2 and 5 failed during testing.
- For every **1·C** rise in temperature the voltage drops by **0.6** V approximately.

Ideality Factor Extraction

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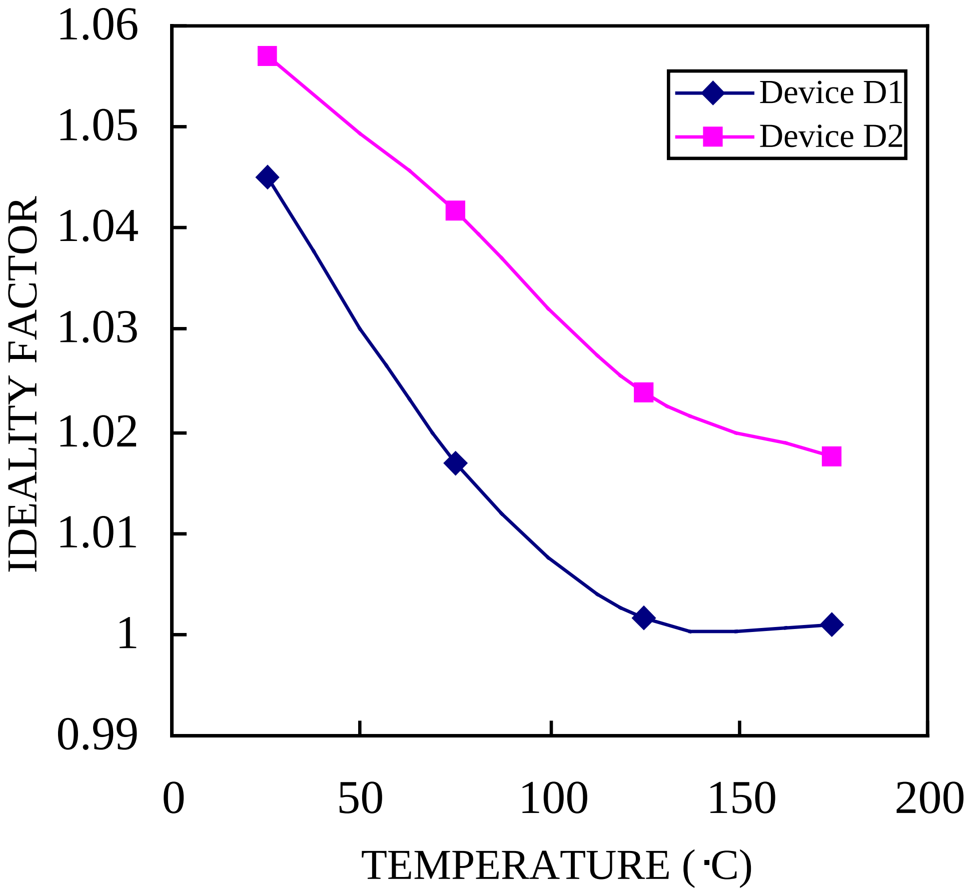


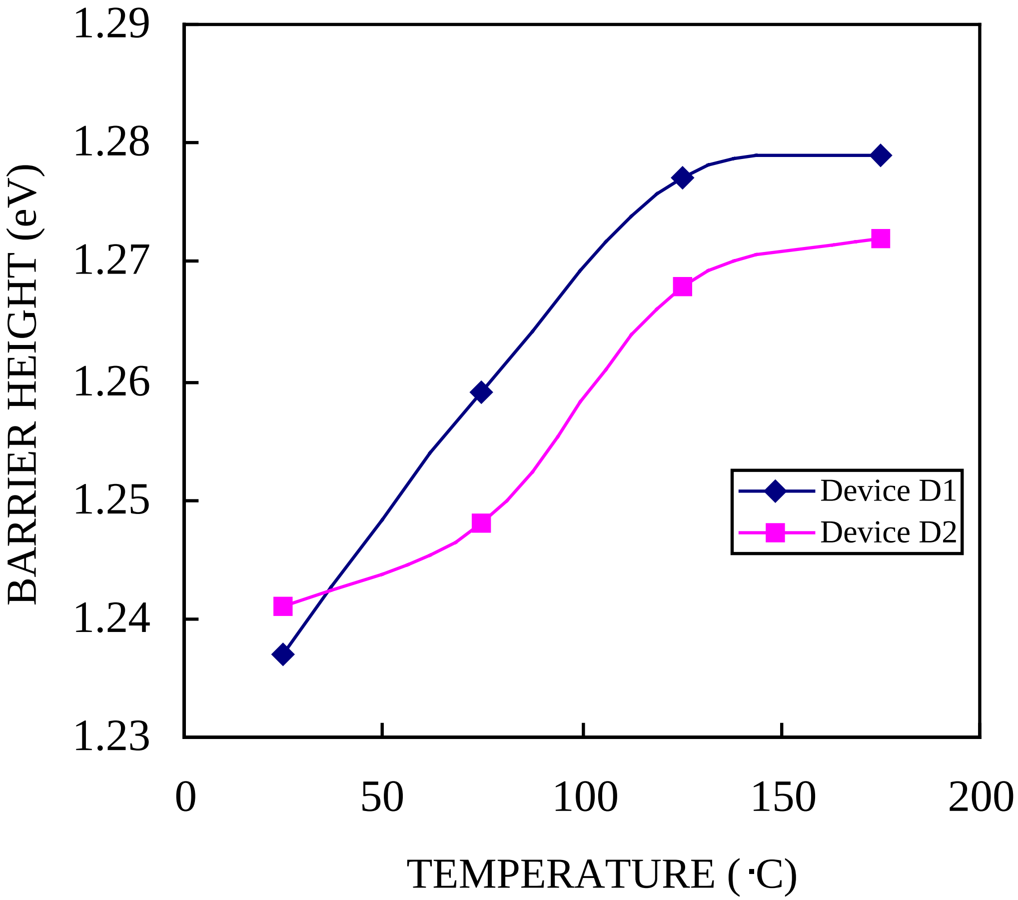
Ideality factor was extracted from the expression for diode forward current

$$n = \frac{1}{\dfrac{\partial(\ln I_F)}{\partial V_F} V_T}$$

Ideality factor approaches unity with increase in temperature.

- Thermionic emission current contribution is more at higher temperatures

Barrier Height from forward IV



Since **n ≡ 1** the barrier height was extracted using the simplified expression for J_S

$$\phi_B = V_T \ln\left(\frac{A^{**}T^2}{J_S}\right)$$

Where

A^{**} is Richardson's constant

V_T is the Thermal Voltage

Barrier Height from C-V Characteristics

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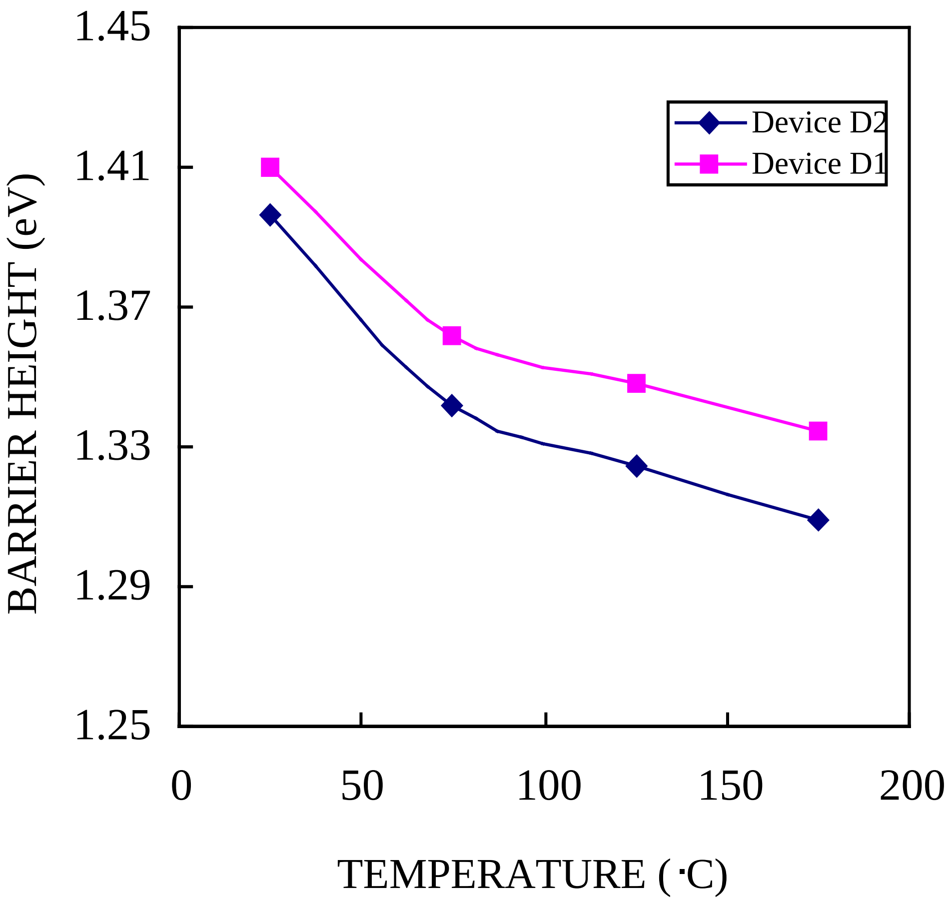


V_i is voltage intercept $(1/C^2)$-V plot
V_{bi} is the built in voltage

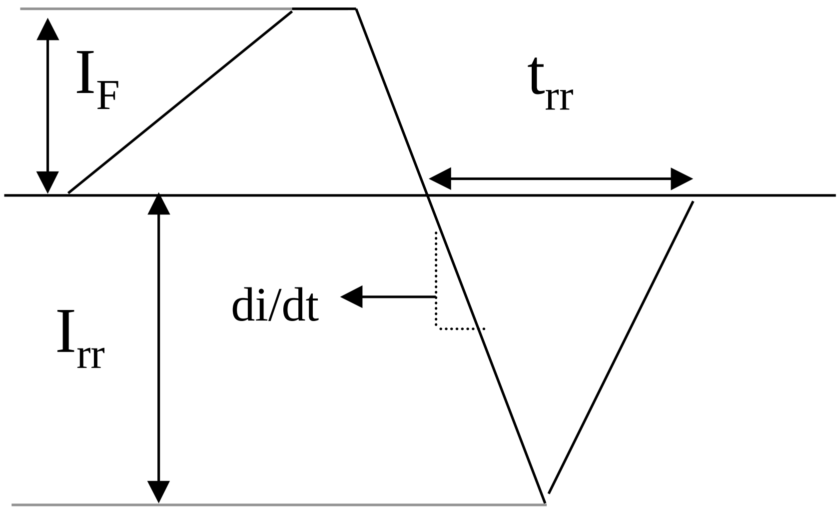
- Doping concentration and device Area were provided.
- Using the device area and the slope of the $(1/C^2)$-V plot the doping was extracted from the expression for Capacitance.

$$C = A\sqrt{\frac{q\varepsilon_S N_D}{2(V_R + V_{bi} - \frac{kT}{q})}}$$

- Extracted value of doping was then used to estimate the barrier height

$$\phi_B = V_i + \frac{kT}{q} + \frac{E_G}{2q} - \frac{kT}{q}\ln(\frac{N_D}{n_i})$$

Reverse Recovery Measurement Procedure



- Devices Under Test (DUT)
  - D1
  - D2

- Measurements were performed at:
  - Three different forward currents (2A, 4A and 6A)
  - Three different temperatures (25 ·C, 75 ·C, 125 ·C)
  - Three different bus voltages (200V, 250V,300V)

Test Circuit

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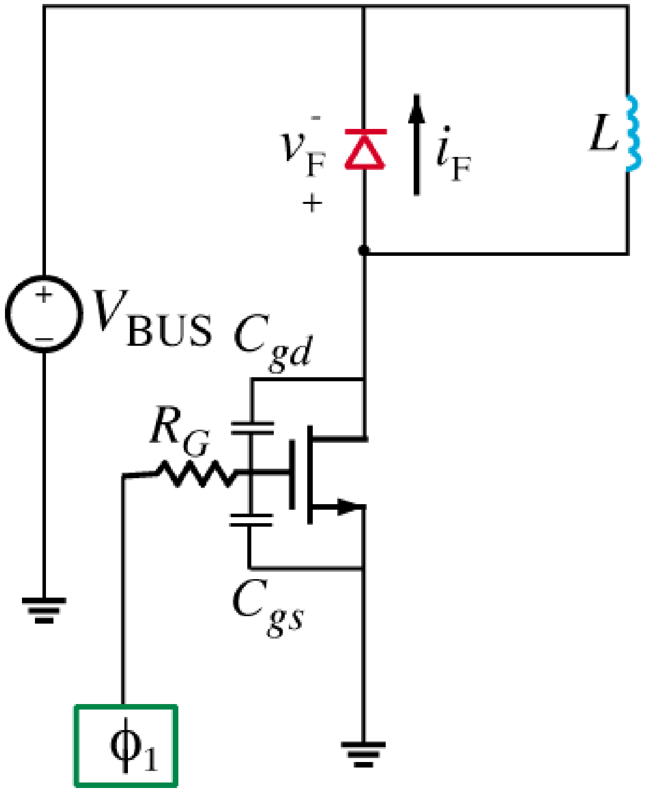

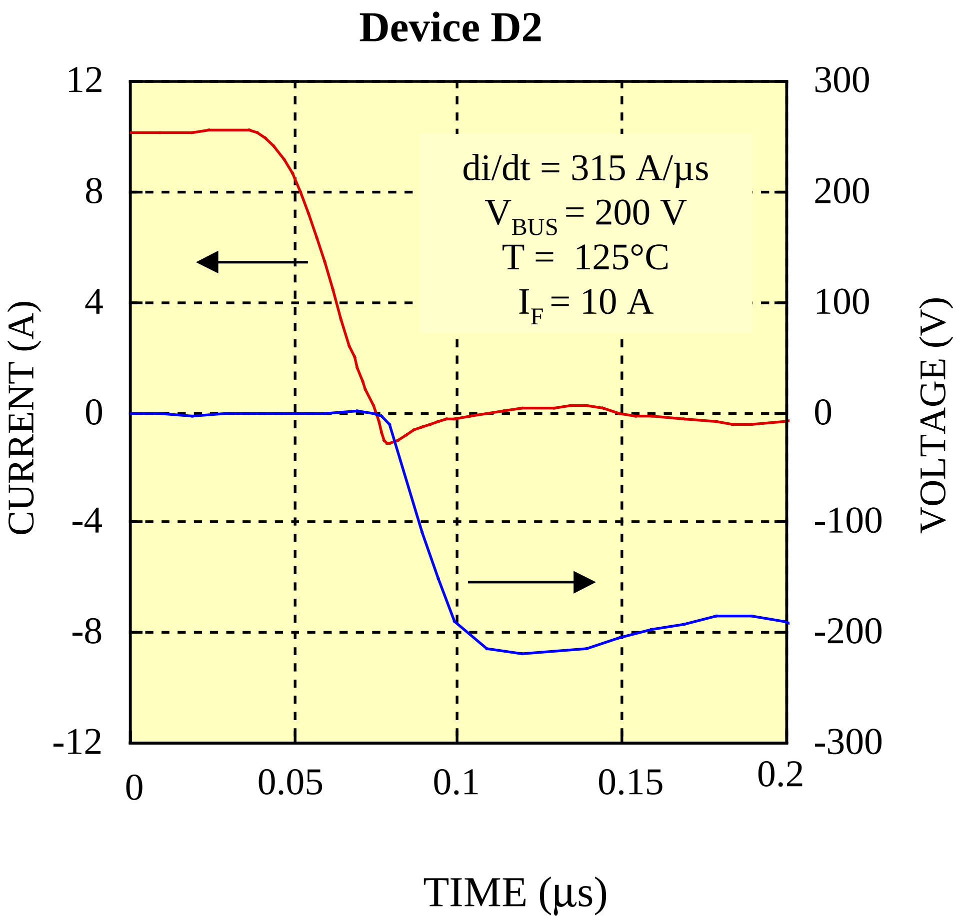

Measured Results

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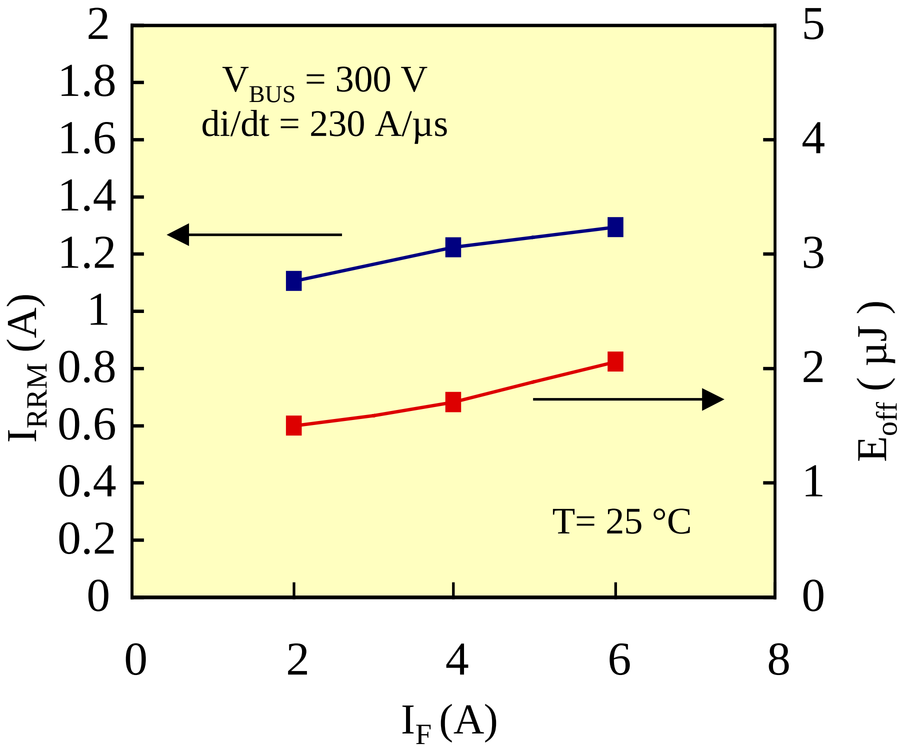
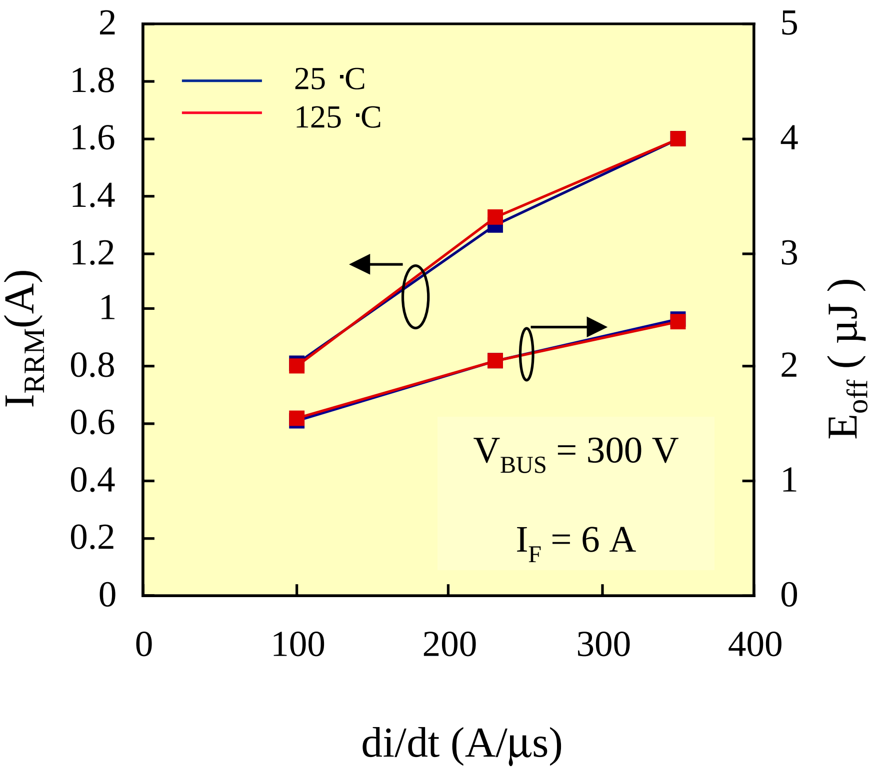
Device D1





PERG Power Electronics Reliability Group

Measured Results

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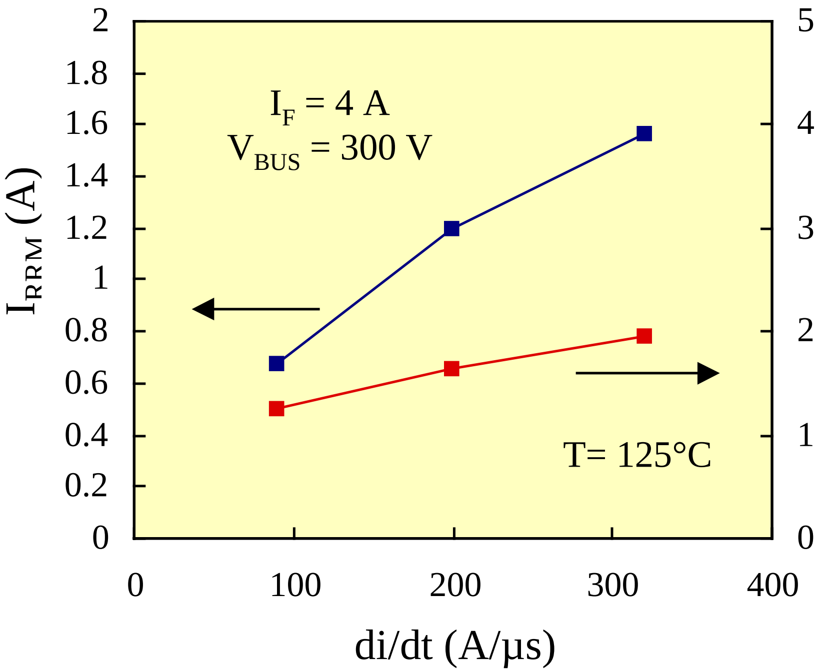
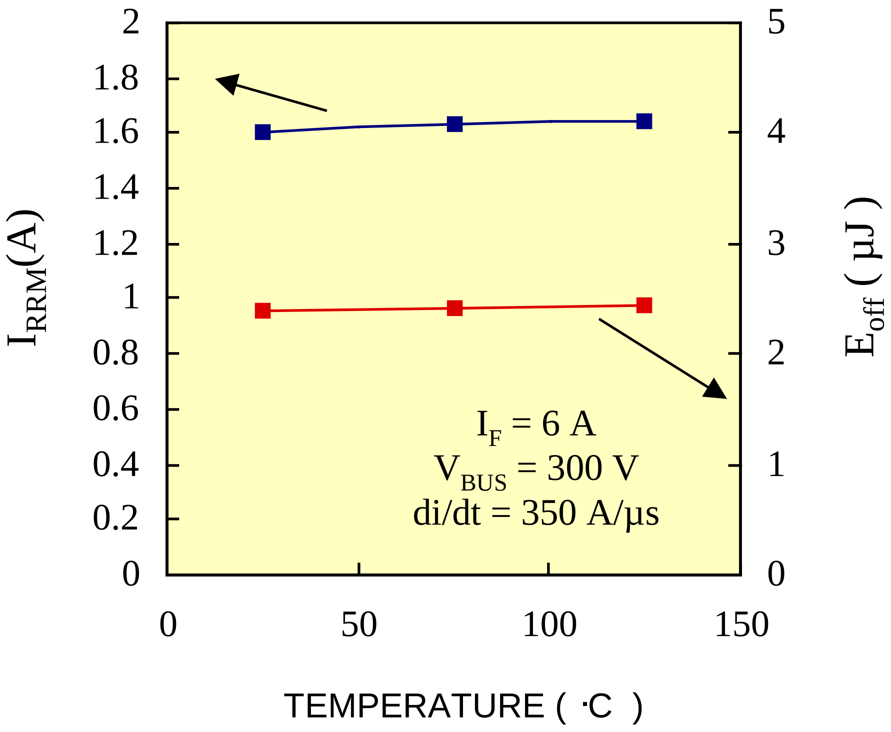
Device D1





Measured Results

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and Computer Science
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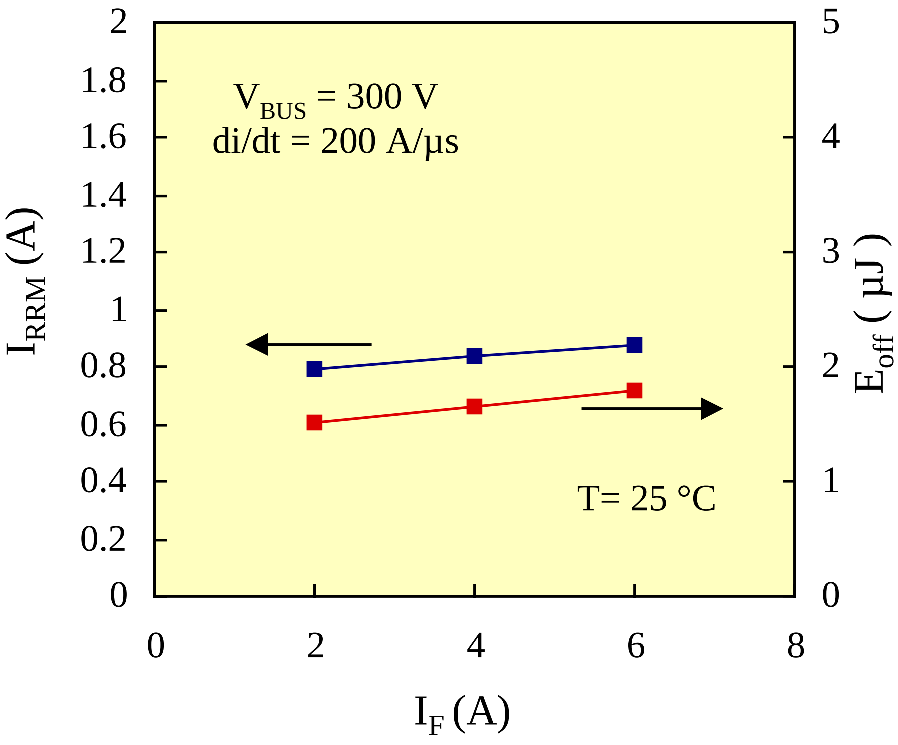
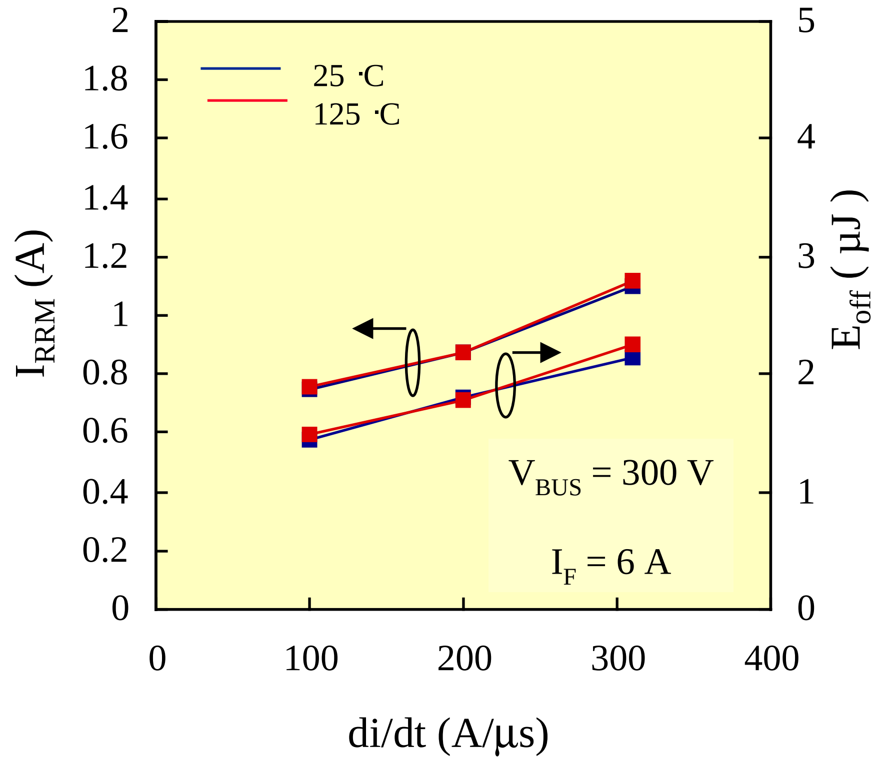
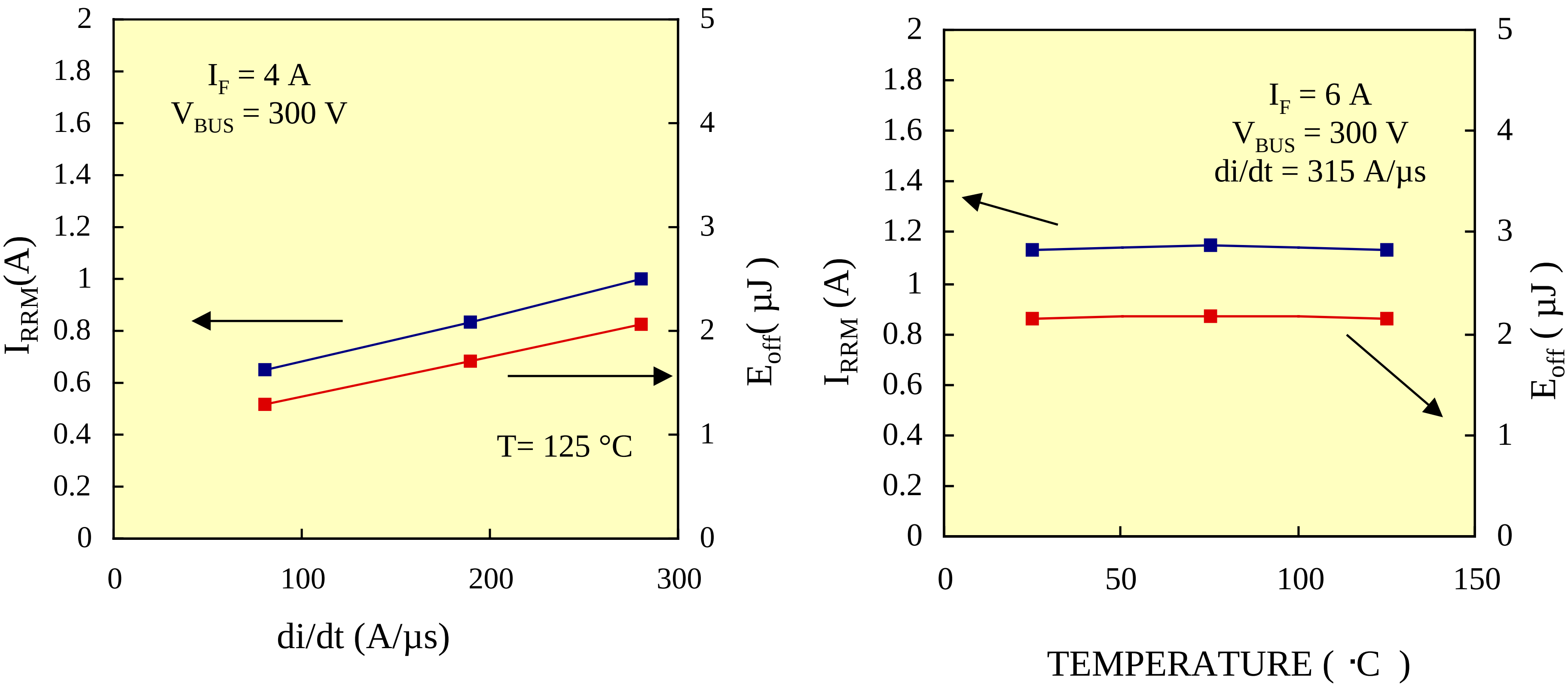
Device D2





Device D2



2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
5
4
3
2
1
0
I_F = 4 A
V_{BUS} = 300 V
T= 125 °C
I_{RRM}(A)
E_{off}(µJ)
0
100
200
300
di/dt (A/µs)
I_F = 6 A
V_{BUS} = 300 V
di/dt = 315 A/µs
I_{RRM} (A)
E_{off} (µJ)
0
50
100
150
TEMPERATURE (·C)

Conclusion

- SiC Schottky diodes show promise for SMPS applications.
- Needs further investigation in key SMPS circuits
- SiC device reliability needs to be investigated in detail.